Energy Research and Development Division
FINAL PROJECT REPORT

ADVANCED AUTOMATED HVAC FAULT DETECTION AND DIAGNOSTICS COMMERCIALIZATION PROGRAM

- Web-Enabled Automated Diagnostics
- AHU and VAV diagnostics
- Advanced Packaged Roof-top Unit
- Rooftop Unit Diagnostics
- SpeciFlow™ Technology
- Market Connections

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

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ABSTRACT

The goals of the Advanced Automated Heating, Ventilation and Air Conditioning Fault Detection and Diagnostics Commercialization Program were developing and demonstrating advanced fault detection and diagnostic methods for cooling, heating, and ventilating systems, developing more advanced and fault resistant heating, ventilation and air conditioning equipment, and working directly with manufacturers to implement improvements and innovations in commercially available products.

The project teams worked to further develop innovative fault detection and diagnostic techniques and systems to be integrated with heating, ventilation and air conditioning equipment systems and controls. The projects included field demonstrations to document the performance and cost advantages of these systems, and developing and distributing information products to market decision makers.

The major results of this research were:

- Creating a web-enabled heating, ventilation, and air conditioning automated diagnostics system that detects and reports significant faults.
- Developing automated methods for determining and setting appropriate control factors for assuring valid detecting and reporting of faults and avoiding or minimizing false reporting of faults.
- Creating a specification for a cost-effective advanced packaged rooftop air conditioner.
- Developing enhanced fault detection and diagnostic methods.
- Making technical improvements to an airflow measurement device to increase accuracy and improve data input and output.

Keywords: automated diagnostics, automated fault detection, automated reporting, fault detection and diagnostics, HVAC fault detection and diagnostics, web-enabled diagnostics, web-enabled reporting

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Over 28% of the electricity used in California commercial buildings is for air-conditioning, heating, and ventilation. At least 10% of this energy is wasted due to excessive run time and problems in the HVAC equipment and controls.

Project Purpose

The overall goals of the Advanced Automated Heating, Ventilation and Air Conditioning (HVAC) Fault Detection and Diagnostics Commercialization Program were improving indoor environmental quality and reducing energy use, peak demand, and pollution. The specific goals of the research included:

- Developing and demonstrating advanced fault detection and diagnostic (FDD) methods and measurement equipment for cooling, heating, and ventilating systems.
- Developing and demonstrating more advanced and fault resistant HVAC equipment.
- Working directly with manufacturers to implement improvements and innovations in commercially available equipment.

This Program is a continuation of the Energy Efficient and Affordable Small Commercial and Residential Buildings PIER Buildings Program, the Integrated Energy Systems: Productivity and Building Science Program, and other PIER buildings research projects.

Project Results

The project teams worked with major manufacturers to further develop innovative FDD techniques and systems that will be integrated with HVAC systems and controls. The projects included field demonstrations to document the energy performance and cost advantages of these systems, and developing and distributing information products to market decision makers.

The HVAC FDD program consisted of five technical projects and one market connection project. The results from each project are summarized below.

The Web-Enabled Automated Diagnostics Project created a web-enabled HVAC automated diagnostics system that detects and reports significant faults in air handlers, chiller, boiler, and cooling tower systems, including associated fans and pumps. The ENFORMA Building Diagnostics FDD application has been demonstrated in over a dozen commercial buildings. The application features are being enhanced and marketing to end users and to service providers continues.

The Air-Handling Units (AHUs) and Variable-Air-Volume (VAV) Box Diagnostics Project developed automated methods for determining and setting appropriate control factors to assure valid detecting and reporting of faults and avoiding or minimizing false positive fault reporting. Three major control component manufacturers have embedded AHU and VAV Box Diagnostics in selected controller components. The National Institute for Standards and

Technology (NIST) worked closely and collaboratively with the HVAC controls manufacturers on field test demonstrations to ensure that product innovations were functional and practical.

The Advanced Packaged Rooftop Unit Project worked in close collaboration with two major rooftop unit (RTU) manufacturers and other industry stakeholders to create a specification for a cost-effective advanced packaged rooftop air conditioner. The Project developed cost/benefit analyses to document the specific benefits of each improvement. The advanced features were added to a commercially available RTU and laboratory tested to evaluate the improvements. Working with a Technical Advisory Group and market transformation organizations, the researchers publicized project results to electric utilities, equipment manufacturers, and end users.

The Rooftop Unit Diagnostics project developed enhanced FDD methods through laboratory testing at Purdue University. These FDD methods were embedded in selected controller components, which were then deployed in field demonstration sites for evaluation. Field Diagnostics Services, Inc. worked with several original equipment manufacturers (OEMs) to investigate the commercialization and manufacturing feasibility of FDD-enabled unit controllers and networked information systems.

The SpeciFlow™ Technology Project made technical improvements to an airflow measurement device to increase its accuracy at high damper opening positions and improve the data input/output (I/O) to accelerate its entrance into the marketplace. Greenheck Corporation has licensed the technology and is marketing an airflow measurement damper assembly using SpeciFlow Technology.

The Program Market Connections Project provided guidance to each Project to improve the market focus of the Program and increase public awareness of the products, technologies, and practices developed in the Program.

Project Benefits

The results of these projects will benefit California by improving indoor environmental quality, and reducing energy use, peak demand, and pollution.

CHAPTER 1: Introduction

1.1 Background and Overview

The goals of the Advanced Automated HVAC Fault Detection and Diagnostics Commercialization Program were to:

1. Develop and demonstrate advanced fault detection and diagnostic methods and measurement equipment for cooling, heating, and ventilating systems,
2. Develop and demonstrate more advanced and fault resistant HVAC equipment, and
3. Work directly with manufacturers in order to implement improvements and innovations in commercially available equipment.

The desired outcomes were improved indoor environmental quality, reduced energy use, reduced peak demand, and reduced pollution for the citizens of California. Over 28% of the electricity used in California commercial buildings is air-conditioning, heating, and ventilation. At least 10% of this energy is wasted due to excessive run time and problems in the HVAC equipment and controls.

This Program is a continuation of the Energy Efficient and Affordable Small Commercial and Residential Buildings PIER Buildings Program, the Integrated Energy Systems: Productivity and Building Science Program, and other PIER buildings research projects.

The project teams in this Program have worked with major manufacturers to further develop innovative FDD techniques and systems that will be integrated with HVAC systems and controls. The projects include field demonstrations to document the energy performance and cost advantages of these systems, and develop and distribute information products to market decision makers. The Program has the following related goals or desired outcomes:

The next generation of packaged and built-up HVAC systems and controls will have either on-board diagnostics or logged data sufficient to allow analysis by a supervisory building control system.

Information about FDD enabled components and equipment will be available for use in HVAC engineering and technician training programs.

Building automation vendors will include FDD reporting in their products.

Commercial building owners and operators will use automated FDD reporting to correct problems in their building HVAC systems and reap corresponding benefits in better building environments, increased equipment life, and reduced energy use and costs.1.1.1 Heading

1.2 Web-Enabled Automated Diagnostics (Project 2)

A potential barrier to widespread use of continuous HVAC system commissioning and diagnostics is the availability of data from the building management systems. To reach the largest customer base possible, two data access paths need to be pursued. Recent versions of Building Automation Systems (BAS) have features that allow easier access to data. However, legacy BASs often do not have robust data access, which leads to the concept of using a data acquisition method separate from the BAS. Furthermore, the portion of existing building stock without BASs or with older BASs that do not have sufficient data points for diagnostics is very large. Using data gathering equipment that is independent of the existing control system is necessary in these cases, however, receiving certain control signals and other available data from the BAS, is also necessary for FDD analysis.

The Web-Enabled Automated Diagnostics Project was conceived as web-enabled software that detects and reports significant faults in air handlers, chillers, boilers, and cooling tower systems (including associated fans and pumps). Several subcontractors under the PIER-funded *Energy Efficient & Affordable Small Commercial and Residential Buildings Program* (PIER Contract # 400-99-011) developed and tested methods to diagnose problems with HVAC system performance. The overall goal of this Project was to integrate the following methods into a suite of web-accessible applications:

NIST's Air Handling Unit Performance Assessment Rules (APAR); and

Diagnostics for chillers, cooling towers, and associated equipment, developed under prior PIER sponsored research (Project 2.5, Pattern Recognition Based FDD) based on the ENFORMA® HVAC Diagnostics Analyzer.

The project objectives and outcomes were:

Develop a web enabled HVAC automated diagnostics system that detects and reports significant faults in air handlers, chillers, boilers, and cooling tower systems

ENFORMA Building Diagnostics was successfully developed, including diagnostics on the listed components. It is an application that uses the Tridium Niagara AX platform for access to legacy building automation systems.

Demonstrate the diagnostic system in at least 3 commercial buildings

ENFORMA Building Diagnostics was demonstrated in six buildings during the Project.

Market the diagnostic system as a commercial product both directly to customers and to service providers.

Licensing of ENFORMA Building Diagnostics for demonstrations and pilot programs started in 2007. Over a dozen installations have been completed.

Project development and research showed that in order to achieve wide spread market adoption ENFORMA Building Diagnostics should concentrate on the following three initiatives:

1. Integrate EBD into the commissioning/re-commissioning process as a tool.

2. Develop wizard applications for installation and software set up to reduce the need for specialized staff and/or training.
3. Develop a well-documented enterprise-wide installation (i.e. 500 sites) in one of the major market segments (e.g. Corporate Real Estate).

1.3 AHU and VAV Diagnostics (Project 3)

Fault detection and diagnostic (FDD) methods that can detect common mechanical faults and control errors in air-handling units (AHUs) and variable-air-volume (VAV) boxes were developed and commercialized. The tools are sufficiently simple that they can be embedded in commercial building automation and control systems and rely only upon the sensor data and control signals that are commonly available in these systems. AHU Performance Assessment Rules (APAR) is a diagnostic tool that uses a set of expert rules derived from mass and energy balances to detect faults in air-handling units. VAV box Performance Assessment Control Charts (VPACC) is a diagnostic tool that uses statistical quality control measures to detect faults or control problems in VAV boxes.

This report describes the transfer of the FDD methods from research to commercial use. An interface between the FDD tools and the building operator is introduced. Results are presented from a multiple site field demonstration in which APAR and VPACC were embedded in commercial AHU and VAV box controllers. Robust FDD parameters are tabulated for both APAR and VPACC. The parameters, which eliminate the need for site-specific configuration, were developed based on experience from the field demonstration.

The Project Outcomes include:

A robust FDD application was developed using the APAR and VPACC rule sets

FDD code was developed using several manufacturers' application programming languages. Robust sets of parameters for APAR and VPACC were tabulated to enable the commercial use of these FDD tools without the collection and analysis of trend data from each potential installation. Recommended values for the parameters were determined through trial and error at multiple field test sites and the resulting values were compiled and tabulated. For users who need or prefer to determine site-specific parameters, procedures to do so were developed and documented.

The application was adapted to 8 sites. The data was trended and, where applicable, the data was accessed weekly through the internet, otherwise it was downloaded on site.

The first step was to gather specifications from the existing site and adapt the application to work with the existing structure. Then the control application was modified to incorporate the FDD algorithms and the data was trended along with the results from the FDD algorithm.

The FDD tools in the field performed as hoped and identified faults at every site

Multiple field sites were established to test APAR and VPACC embedded in commercial HVAC equipment controllers. The test was quite successful: a variety of mechanical and control faults have been detected, diagnosed, and in many cases, repaired.

The viability of deploying FDD as an integral component of the HVAC control system has been demonstrated. Based on feedback from users at the field sites, modifications have been made to enhance the usability and robustness of the FDD tools. In some cases, the local representative of the manufacturer of the control system was involved in the setup and operation of the test site. Feedback from these manufacturers' representatives, who will ultimately be responsible for installing FDD in their customers' buildings, was used to make the installation procedure more time- and resource-efficient and minimize the amount of site-specific configuration required.

1.4 Advanced Package Rooftop Unit (Project 4)

Existing rooftop units have consistent and documented energy waste problems. By combining the expertise of the members of the project's Technical Advisory Group (TAG) and the research team, and with the funding provided by the California Energy Commission (CEC), we can help solve many of these problems. We further believe that we can identify particular "features" that an ARTU should have, and that incorporating these features in a demonstration rooftop unit would provide value to the manufacturing, contracting, utility and energy communities.

The project goal was to develop, test and demonstrate an ARTU prototype of 5 ton cooling capacity that addresses many of the energy and ventilation problems found in commercial building mechanical systems. Features of the ARTU will include improved outdoor air control, improved economizer reliability, diagnostics and troubleshooting capability, and fault-tolerant design. The end result will be a unit that operates according to prevailing ventilation standards, reduces energy use and requires less maintenance.

The ARTU project builds on previous research conducted under NBI PIER Element 4, Integrated Design of Small Commercial HVAC Systems (CEC Contract 400-99-012). That program published results of field studies in which more than 200 rooftop units, none of which were more than four years old, exhibited a number of problems with poor economizer operation, improper refrigerant charge, low air flow, high fan power and cycling fans, and other control issues. Such issues often go undetected by building owners and even service personnel.

The program also produced performance guidance for designers and operators on ways to improve the efficiency and operations of small package HVAC units. Many of these improvements could be integrated into a new "advanced" unit that would directly address performance and market impact objectives.

Features of the ARTU will demonstrate the four main goals of the project:

1. Improved outdoor air control,
2. Improved economizer reliability,
3. On-board self-diagnostics and troubleshooting capability, and
4. Fault-tolerant design.

Features will be described that address:

- Economizer Improvements

- Fan Improvements
- Unit Efficiency
- Refrigeration Cycle Improvements
- Fan Controls
- Refrigerant Control
- Thermostat Capability
- Sensors
- Installation & Check-out Capability
- Advanced Monitoring
- Advanced Diagnostics

Project Outcomes included

Technical Advisory Group (TAG)

A ten-member ARTU TAG participated in two meetings/conference calls and numerous email communications.

Identify ARTU Product Features

In total, 66 features were researched for this task. The term "Features" refers to physical and programmable changes made to AHU's to increase performance, or reliability. There are 3 different levels of features. Level 1 consists of features that are presently commercially available and make up the foundation of the ARTU. Level 2 includes everything in level one in addition to features that further increase efficiency and performance but may not be readily available in today's market. Features in level 2 that are not available on the market may be under development. The features in level 3 are suggested performance based measures for future development. Of the 66 features investigated, 21 were level 1, 17 were level 2, 7 were level 3 and 21 features were not incorporated.

The CEE "specification" was more a proposed list of provisions or "features" for an advanced rooftop unit than a traditional (i.e., CSI format) specification for air handling units. CEE divided their features into three "Tiers," but the features are now sorted into three "Levels" since the "Tier" terminology conflicts with other meanings in the industry. The term "Level" has the following definitions:

LEVEL 1 is a set of <u>features that are all currently available</u> on the market, can be requested today, and are fundamental to improving field efficiency and performance. Although some of these features are not routinely purchased with basic systems today, features in this level are intended as the foundation requirements of an advanced roof top unit.

LEVEL 2 incorporates the features in Level 1, plus <u>additional design features</u> that create a new Advanced Rooftop Unit (ARTU) that can deliver greater field efficiency and performance. <u>These features may not be readily available on the market, but some are a part of a development and testing project</u> underway through California Public Interest Energy Research and manufacturing partners.

LEVEL 3 is a set of proposed performance-based measurements for future specification development. In the course of exploring in-field performance problems affecting efficiency, CEE found that there was a lack of performance-based measures and test protocols to address these aspects of performance. As a result, CEE identified a number of measures that would be useful in developing a performance-based specification.

Cost-Benefit Assessment

The costs and benefits for 36 features were assessed for to a 5-ton electric cooling, gas heating rooftop unit, a common HVAC system found in small commercial installations.

Develop Prototype ARTU

During the prototype development phase of the ARTU project, a 5-ton Carrier rooftop unit, Carrier model 48PG ("Centurion" series), was modified to incorporate as many ARTU features as possible. The stock unit already includes many ARTU features, and is Carrier's premium rooftop unit.

Develop Test Plans and Test Prototype Unit in a Laboratory

This prototype ARTU was tested at Southern California Edison's Refrigeration & Thermal Testing Center (RTTC) in Irwindale, CA. The test results demonstrate that ARTUs can be developed and that some RTUs available in the market now have many ARTU features.

1.5 Rooftop Unit Diagnostics (Project 5)

Automated fault detection and diagnostics (FDD) applied to HVAC equipment has the potential to improve energy efficiency and comfort and reduce operating and service costs. In earlier work, the principal investigators developed FDD methods for packaged air conditioning equipment that has resulted in the development of a successful commercial product. However, ultimately it is expected that diagnostics will be embedded in HVAC equipment at the factory.

In short, the goals of this PIER-funded Project were:

- Embed FDD methods in selected controller components from one or two major control component manufacturers and deploy these in field demonstration sites for evaluation.
- Work with manufacturer(s) to develop network systems and information technology to effectively communicate equipment conditions to facilities and service personnel.
- Deploy these FDD-enabled unit controllers and networked information systems in field demonstration sites for evaluation and refinement.

The project was a collaborative effort between Purdue University, Field Diagnostic Services, Inc. (FDSI), and Honeywell, Inc. The development of virtual sensors and improvement of diagnostic algorithms was largely performed by Purdue University. Development of hardware, implementation of diagnostic algorithms, field trials, and development of promotional and training materials was done primarily by FDSI. Honeywell provided technical and financial support for the prototype development and field studies. Additional leverage occurred through a concurrent project that was funded by the Department of Energy.

Project Outcomes include:

Embed FDD methods in selected controller components from one or two major control component manufacturers and deploy these in field demonstration sites for evaluation.

Some packaged HVAC systems with onboard diagnostic capabilities were reviewed and the most advanced unit identified was the Centurion™ unit with ComfortLink™ controls introduced by Carrier in 2005. The unit has approximately 40 alarm codes including identification of some refrigeration faults, airside faults, and control faults; however, the diagnostics were supplemented by the FDSI FDD product as part of the CEC sponsored Advanced Rooftop Unit project also funded as part of this PIER Program.

Work with manufacturer(s) to develop network systems and information technology to effectively communicate equipment conditions to facilities and service personnel.

One of the long-term goals of this project was to fully integrate the FDD technology within an OEM's control system, rather than being a retrofit FDD product that must be installed in the field. Experience during the project has demonstrated that the time frames for working with equipment manufacturers in order to get them to embed FDSI's FDD technology as part of their product line are much longer than the time period for this project.

In addition, FDSI has held discussions with at least four other OEMs regarding various embedded product proposals, and FDSI has engaged a retired OEM executive as a consultant. One of the OEM discussions is with a manufacturer of walk-in coolers and freezers.

FDSI has also explored the integration of the FDD technology with building automation systems. For example, at the end of the field trial of the retrofit embedded product at UC San Diego, options were explored for integrating the FDD monitoring system with the Johnson Controls' Metasys building management system in place at UCSD. The simplest form of integration would be merely setting up a Metasys workstation so that it could toggle to the FDSI Web page for the FDD monitoring data. For a tighter integration, the best path might be through the alignment of Web Services (a software system, or collection of Web programmable interfaces, designed to support computer-to-computer interaction)

Deploy these FDD-enabled unit controllers and networked information systems in field demonstration sites for evaluation and refinement.

From 2004 to 2007, the various versions of the retrofit embedded FDD product were field-tested at a small number of sites. The field sites participating in the project for the majority of the time were three California universities, and a Honeywell site in Georgia, with an additional off-and-on site at a retail store near FDSI's headquarters, although earlier, several Walgreens sites were also participants in field-testing the "VM" embedded system, which was a predecessor to the eventually developed Sentinel product.

Conclusions

Market Penetration

The short-term goal-to-market strategy for Sentinel is to sell retrofits into existing HVAC equipment in the field. FDSI's primary target is national retail chains where there is already significant penetration with its portable Service Assistant product, partially facilitated by wide-scale HVAC tune-up program utility incentives. The tune-up provides a detailed assessment of the condition of all the customer's equipment and helps target a good Sentinel business case on the poorer performing sites and units.

FDSI has developed a management system where FDSI technology is used to assess the condition of equipment in the field and the effectiveness of service work in support of utility tune-up programs. This management system is being expanded beyond the utility programs directly to the national chains. It provides an excellent platform inserting Sentinel technology when appropriate to best manage the customer's equipment. As the value of the technology proves itself and through OEM and building control system integration efforts, the customers can more cost effectively get Sentinel installed in the factory so it can plug into the management infrastructure after installation.

Savings Benefits

The business case analysis included predicted savings (energy and maintenance), system installed cost, and simple payback. Based on the design of the initial product release the energy savings associated with addressing faults identified by the FDD system were estimated as 19% of the cooling energy use. The maintenance cost savings were estimated as 33% of the annual cost per unit of $1000, or $333 per unit per year. The installed system cost for a site with five units (single compressor) was $6,939. The building size varied from 5,000 square feet to 30,000 square feet and the number of units per building varied from 4 to 8 based on the building type (and size). The FDD system is most cost effective for buildings with four or more units. Based on the various building types that estimated simple payback period varied from 1.9 to 4.5 years. The estimated payback period for Small Offices was 3.3 years and the payback period for Retail Stores was 3.7 years.

1.6 SpeciFlow™ Technology (Project 6)

SpeciFlow™ airflow control technology works by integrating pressure pickups, a temperature sensor, and a position sensor with stock control dampers. An empirically determined calibration curve embedded in a programmable controller is used to relate pressure, temperature, and position to flow rate. The controller adjusts the position of the damper so that the computed flow rate tracks the desired flow rate. Although SpeciFlow™ technology could be applied to any airflow measurement and control application that requires a control damper, the target application is direct measurement and control of outdoor airflow rate.

SpeciFlow™ technology performs better than the leading product of its kind on the market (Ruskin's IAQ50). However, testing and conversations with Federspiel Controls' market partner (Greenheck Fan Corporation) has revealed a need for further development in three areas: calibration, sensitivity to non-uniform flow, and design features. This project involved three tasks, one aimed at each of these three areas.

Project Outcomes included:

Generic calibration curve

We compared the calibration curves of each identical pair of dampers. We computed an "average" calibration curve for each pair from the four sets of calibration data for that pair, and then computed the relative accuracy using the average calibration curve for all face velocities between 300 feet per minute and 2000 feet per minute. The relative accuracy is the difference between the measured airflow and the airflow predicted using the average calibration curve as a percent of the measured flow. The results show that most of the time manufacturing variability will be small enough to use a nominal calibration curve, except at marginally open positions (e.g., 25% open). Damper accuracy should be checked prior to shipping, particularly at marginally open positions.

Correction for non-uniform flow

The original approach was to investigate two methods for detecting and correcting for non-uniform flow when a control damper is more than 70% open. The first approach involved conducting tests on control dampers with additional instrumentation designed to provide the necessary information to detect and correct for non-uniform flow. The second method was attempted to correct for non-uniform flow by measuring the non-uniformity of the static pressure field at the leading edge of the damper with two pressure sensors.

The results found, for the first method, the four-sensor array of pressure pickups arranged to average the velocity in each quadrant of the damper is inadequate for correcting for the non-uniform flow resulting from strong upstream disturbances such as louvers. The second method where two additional sensors used to measure the pressure gradient at the leading edge of a damper may be used to correct for non-uniform flow. However, separate corrections are necessary for each combination of direction (horizontal and vertical) and sign of the pressure gradient. This would increase the calibration effort by a factor of five, which would probably make this method more expensive than simply using a flow straightener. A pressure-dependent flow coefficient can be used effectively to correct for the changes in the velocity distribution that are associated with changing average velocity between the damper blades.

Engineered for advanced market adoption

Based on input from Greenheck and feedback from their sales representatives, we developed a list of new input-output specification for the SpeciFlow™ controller. The controller has been adapted to comply with every technical specification.

Conclusions

Most of the time manufacturing variability will be small enough to use a nominal calibration curve, except at marginally open positions (e.g., 25% open).

When comparing the errors on dampers A through F only two of the 76 points for (A,B) are outside the specification of 5% of reading, while none of the points for (E,F) are outside the specified accuracy range. The agreement between C and D is not as good, with 19% of the points outside the specified range.

The results also show that even when dampers have the same calibration curve, the small differences from damper to damper may cause the accuracy to be outside the specification when the damper is marginally open (e.g., 25% open). This is because the face velocities under these conditions are low even at the highest pressure that the pressure sensor can read. This implies that each damper must be calibrated at this position or at least checked for accuracy at this position prior to shipping.

The use of additional sensors to compensate for non-uniform flow is inadequate with 4 sensors and becomes two expensive with two additional sensors on the leading edge of the damper. A pressure-dependent flow coefficient can be used effectively to correct for the changes in the velocity distribution that are associated with changing average velocity between the damper blades.

A four-sensor array of pressure pickups arranged to average the velocity in each quadrant of the damper is inadequate for correcting for the non-uniform flow resulting from strong upstream disturbances such as louvers.

Two additional sensors used to measure the pressure gradient at the leading edge of a damper may be used to correct for non-uniform flow. However, separate corrections are necessary for each combination of direction (horizontal and vertical) and sign of the pressure gradient. This would increase the calibration effort by a factor of five, which would probably make this method more expensive than simply using a flow straightener.

A pressure-dependent flow coefficient can be used effectively to correct for the changes in the velocity distribution that are associated with changing average velocity between the damper blades.

The new design of the SpeciFlow™ controller meets all of the technical specifications.

Based on input from Greenheck and feedback from their sales representatives, we developed a list of new input-output specification for the SpeciFlow™ controller. The controller has been adapted to comply with every technical specification.

1.7 Market Connections (Project 7)

The objectives of Market Connection Project are to

- *Facilitate and accelerate the successful development and introduction of the advanced fault detection and diagnostic methods into commercial HVAC products that will be deployed in California buildings and*
- *Promote the development of other equipment and techniques for the commercial market to improve indoor environments and energy efficiency.*

The Market Connections component was incorporated to help guide the market focus of the Program to increase the adoption and public benefits impact of the projects products and results.

Successful results were to include:

Private sector adoption of technologies and practices from the Program.

Regulatory and voluntary mechanisms that influence the integration of the results into the market and that exist as a result of this project.

Accomplishing main Market Connection tasks areas and deliverables, including Technology Transfer Plans, Scoping Study, Strategic Partnership, and Market Connection Activities

Conclusions

The Market Connections work was successful in meeting the key FDD Program goals of advancing FDD further into the market and into regulatory arenas in California. NBI's Market Connections activities have helped create momentum that is likely to carry forward as the whole topic of achieving and maintaining building energy performance advances toward goals being established in California and elsewhere to create a path to zero net emission commercial buildings in 2030.

The key challenges remain of transforming the way buildings are designed, controlled, operated and maintained. As noted there is a lack of common definition or industry standards of what constitutes FDD capabilities within control systems in larger buildings. In smaller commercial buildings, effective control strategies are not obvious to many building operators. Limited attention by owners often means that potential problems with equipment performance are not acknowledged until something breaks or there is a loud enough occupant complaint about temperature and/or ventilation conditions. This is true for all sizes and types of commercial buildings. The mere presence of FDD information is not sufficient to cause actions to take place in many buildings. Transformation of owner/operator attitudes toward building performance is the critical ingredient in realizing the potential of FDD functionality. This is not a new observation or conclusion. It is a reminder of what remains to be done in the overall building performance market.

FDD is not fundamentally a standalone approach with its own specialized set of tools and black boxes. FDD must be viewed within the overall framework of whole building and subsystem controls, performance monitoring, and HVAC system operations and maintenance.

The US Department of Energy commissioned a 2006 report titled “Energy Impact of Commercial Building Controls and Performance Diagnostics: Market Characterization, Energy Impacts of Building Faults and Energy Savings Potential.”[1]

The study’s authors concluded that generally FDD could save between 5-30% of building energy use. This is a similar conclusion initially made about the energy savings potential of building commissioning, which is itself a diagnostic approach. Given the less than optimal operating conditions found in many buildings, a prominent FDD researcher has noted that savings of 15-30% were likely using diagnostics. Although a more closely bounded estimate is necessary, there is an acknowledgement that the potential energy savings benefits of FDD are not easily calculated, since, ultimately, individuals have to take action based on the information provided by FDD systems. Conditions in management outside the purview of building operations usually dictate the limits of the operations staff’s ability to optimize building energy performance

There are a number of detailed related post-program follow-up recommendations that could be considered in California and nationally. The recommendations here focus mostly on higher level actions within California. The IOUs have the organizational capacity through the Emerging Technology framework to assess the benefits and costs of FDD. Recent regulatory calls in California for substantial IOU support of FDD benefit assessments will help drive FDD toward market adoption.

The recommendations made here closely parallel and support the recommendations recently developed through the CPUC’s Strategic Planning Process and linked to the recently released “Preliminary Energy Efficiency Strategic Plan” by the California IOUs. In addition, the Western Cooling Energy Center, has proposed a comprehensive statewide FDD program that drew upon collaborative work between NBI and WCEC staff. Piecemeal efforts at establishing FDD in the market are less likely to succeed than a more structured, comprehensive statewide approach, such as has been proposed by the Cooling Center.

1.8 Report Organization

The Projects within the Program covered development of FDD methods, hardware, and software ranging from discrete components to systems. Sections 3 through 8 of the Report cover the Project Objectives, Project Approach, Project Outcomes, and Conclusions for each Project.

The HVAC FDD program consists of 6 technical projects and a market connection project. The six projects are:

Section 3: Web-Enabled Automated Diagnostics (Project 2)

Section 4: AHU and VAV Diagnostics (Project 3)

[1] http://www.tiaxllc.com/aboutus/pdfs/energy_imp_comm_bldg_cntrls_perf_diag_110105.pdf

Section 5: Advanced Package Rooftop Unit (Project 4)

Section 6: Rooftop unit Diagnostics (Project 5)

Section 7: SpeciFlow™ Technology (Project 6)

Section 8: Project Market Connections (Project 7)

CHAPTER 2:
Project 2: Web-Enabled Automated Diagnostics

2.1 Introduction

A potential barrier to widespread use of continuous HVAC system commissioning and diagnostics is the availability of data from the building management systems. To reach the largest customer base possible, we believe that two data access paths need to be pursued. Recent versions of BAS have features that allow easier access to data. However, legacy BASs often do not have robust data access, which leads to the concept of using a data acquisition method separate from the BAS. Furthermore, the portion of existing building stock without BASs or with older BASs that do not have sufficient data points for diagnostics is very large. Contractor will concentrate its efforts on the use of data gathering equipment that is independent of the existing control system. However, receiving certain control signals and other available data from the BAS, is also necessary for the analysis.

Several of the Contractor's subcontractors under the PIER-funded *Energy Efficient & Affordable Small Commercial and Residential Buildings Program* (PIER Contract # 400-99-011) developed and tested methods to diagnose problems with HVAC system performance. This project will integrate two of these methods into a suite of web-accessible applications:

NIST’s air-handling unit diagnostics in accordance APAR; and

Diagnostics for chillers, cooling towers, and pumps developed under prior PIER sponsored research (Project 2.5, Pattern Recognition Based FDD) based on the ENFORMA® HVAC Diagnostics Analyzer.

2.2 Project Objective

2.2.1 Project Goals

The goal of this Project is to develop and test a system that can be used to provide on-line HVAC diagnostics to a large population of commercial buildings. The system will also provide a framework that can easily be expanded to implement other diagnostic systems as they are developed.

The objective of this project is to provide access to diagnostic tools previously developed through PIER-funded projects through one or more web-based systems.

The goal of task 2.2 is to develop a concept and specification for the framework of the software. Devise strategies to: 1) migrate each application to operate on a server, and 2) operate with data from any number of customer sites. Develop software for the framework, implement the software conversions of each application, and test each application on data samples.

The specific diagnostics to be implemented are as follows:

2.2.2 Air Handling Unit Diagnostics

The APAR rule set is used to verify that, for each basic mode of AHU operation (heating, cooling with outside air, cooling with outside air and mechanical cooling, and cooling with mechanical cooling only), the system measurements verify the system is efficiently operating in each of these modes. When one or more rules are violated, this is an indication of an anomaly that can be related to system operation, sensor error, or other cause. The complete rule set will be implemented. The currently available explanations associated with sets of violated rules that lead to pinpointing the actual cause of the rule violations will also be implemented. The APAR developers are continually expanding this set of explanations and causes. The types of faults that could potentially be identified by the rule set include the following:

Stuck or leaking mixing box dampers, heating coil valves, and cooling coil valves;

Temperature sensor faults;

Design faults such as undersized coils;

Sequencing logic errors;

Central plant faults affecting the hot or chilled water supply conditions at the AHU coils;

Inappropriate operator intervention.

2.2.3 Chiller and Cooling Tower Diagnostics:

The chiller and cooling tower automated diagnostics that were developed and implemented in a stand-alone software application under the PIER-funded Energy Efficient & Affordable Small Commercial and Residential Buildings Program (contract #400-99-011) include:

Chilled water supply temperature maintenance

Chiller-related equipment schedules

These will be implemented in the on-line diagnostic application. Other diagnostics that were investigated and implemented in a spreadsheet-based test application included interactions between the chiller and cooling tower. These will also be implemented.

Contractor will implement all of the chiller and cooling tower diagnostics using the rule set framework used for the APAR diagnostics. Because the automated chiller and cooling tower diagnostics are based on rules, it will be efficient to reformat them to fit within the structure used for the APAR rule set. The automated diagnostics developed under the previous PIER Program are in Microsoft Excel VBA and are also partially implemented in a C++ application that utilizes a Microsoft Access 2000 database. Neither of these implementations could be directly used by the on-line diagnostic application. Reformatting all the diagnostic rules into a single format will facilitate implementation and maintenance.

The goal of task 2.3 is to integrate the FDD engine with the Tridium Niagara AX platform. The Niagara AX is key to the success of the diagnostic engine, as it will provide a common secure data source for the diagnostic engine developed in this project, regardless of the building and

BAS installed in the building. The data security provided will alleviate many concerns regarding exposing the building BAS to the internet.

The tasks associated with the Tridium system integration include designing the FDD application to work within Niagara AX, automation of data verification (missing data or erroneous data) sensor faults caused by missing sensors, sensor drift, implementation of occupancy schedules which will be used during diagnostics, and creation of all required reports. Data verification is important so that the diagnostic applications provide results on the best data available.

To provide meaningful information to the user, Tridium's system reporting functions will be further developed to include diagnostic and other reports as necessary to maximize the product usability.

2.2.4 Data Acquisition Development

The data acquisition hardware consists of the gateway, the sensors, and the communications links between them. The communication links can be wired or wireless, depending on the application. For example, wired links make sense when the distances are short and/or wiring can be done very inexpensively. Wireless sensors make sense when they are the lowest cost approach. Furthermore, communication between the gateway and appropriate BAS is also part of the data acquisition system.

During this task, the most appropriate sensor technologies will be selected to make the measurements needed by the new applications and the most appropriate method and equipment transfer the data from the building. Data transfer methods could be either via telephone lines or the Internet, or even wireless methods if this turns out to be the most practical solution. Accuracy, durability, ease of use, and cost will be balanced in this process.

It is anticipated that some of the required measurements will require communications with the BAS. One of the largest deciding factors when choosing Tridium was its ability to interface with the large variety of BAS communication protocols. Tridium's Niagara AX is set up to communicate with Lon Works®, BACnet and many other common protocols. There can be significant issues associated with communicating with the BAS, by choosing Niagara AX as our interface these issues will be taken care of.

The second part of task 2.3 is to configure a prototype of the hardware needed for the system by augmenting or modifying existing equipment or developing new equipment, as needed. A prototype version of the updated hardware package will be used for the field tests.

The goal of task 2.4 is to install the hardware at three test sites, consisting of one alpha test site and two beta test sites. Retrieve data and store it on Contractor's server. Alpha phase testing will be at a site geographically close to Contractor. Beta phase testing will be at sites in California. The actual diagnostic engine will be located on Contractor server. Provide the building operator, mechanical contractor, and others needing access to the diagnostics with access to the Contractor's Web site. Set up e-mail notifications to them, as well as to the Commission Contract Manager, as appropriate.

The goal of task 2.5 is to develop a plan to make the knowledge gained, experimental results and lessons learned available to key decision-makers.

The goal of task 2.6 is to create the commercial readiness plan. The plan is to determine the steps that will lead to the adoption of the technologies developed in this project and the commercialization of the project’s results.

2.3 Approach

With the fault detection and diagnostic software already developed, a method for communicating between the BAS and the FDD software was needed. Essentially the Enforma product needed a means with which to listen to the building. Given the large variety of communication protocols used by building automation systems, the cost to develop our own translator would be too large. Three gateway products were reviewed during our investigation. These products represent a sample of the major manufacturers of such devices and illustrate the industry's' approach and pricing to the end user in the marketplace. We examined gateway products from FieldServer, Enflex® and Tridium®.

Tridium’s Niagara AX offered the communication ability that was needed. Niagara AX was installed as a gateway protocol translator for the appropriate BAS drivers.

This approach used third party hardware and software to translate BAS I/O into usable data. These hardware/software packages function as a bridge from the Building Automation System's native protocol to a different protocol such as Ethernet. Many products are a fully functional TCP/IP network host serving as a multi-protocol data gateway to many different devices and a variety of 3rd party systems.

A gateway is a hardware/software bridge that solves interoperability problems by translating the data stream coming from many different devices operating under a number of data protocol configurations. A gateway may also host a BAS and provide data storage. The general configuration of the gateway is a hardware platform with imbedded software, which resides at the site and communicates with the BAS via a variety of options. A portion of the data and diagnostics is saved onboard the gateway to eventually be sent to the central server where the entire building history is archived. The archived data along with the processed diagnostic data is stored on the central server where it is web accessible to clients and engineers.

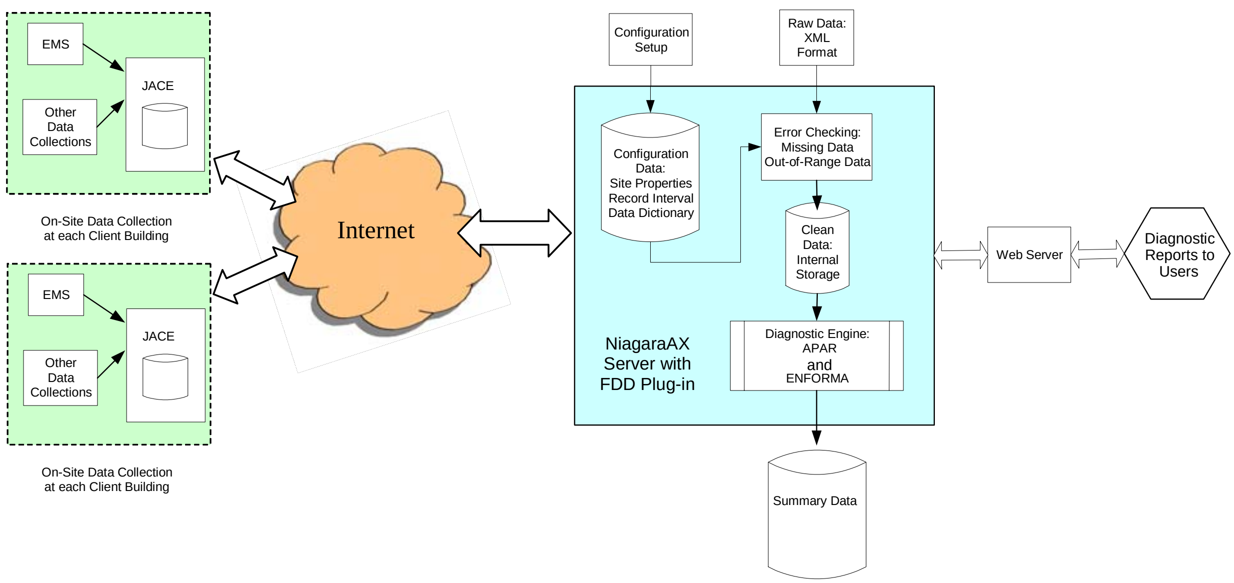
The suite of diagnostic applications will run on a centralized, web-accessible server. Any changes and improvements to the data analysis and diagnostic methods can be quickly and easily implemented at a central location. Contractor has successfully field-tested this concept on buildings in California as part of its work in the California Building Energy Initiative. The primary target market for this suite of applications will be buildings with built-up HVAC systems.

The diagnostic applications will be designed for use primarily in an off-line mode. The purpose of the diagnostic applications is to find problems related to energy waste.

2.3.1 System Architecture

The production version of FDD will normally be installed in a server running NiagaraAX located at the building or campus. This approach will be used for at least one of the California beta test sites. For the alpha test sites in Colorado, since we anticipate that the FDD engine and user interface will be updated frequently based on the results of the field testing, we will centrally locate a Niagara AX server running the FDD plug-in at AEC, and transmit the raw point data from the AX JACE located at each site to the central FDD server over the internet. A representation of this architecture is shown below, in Figure 1.

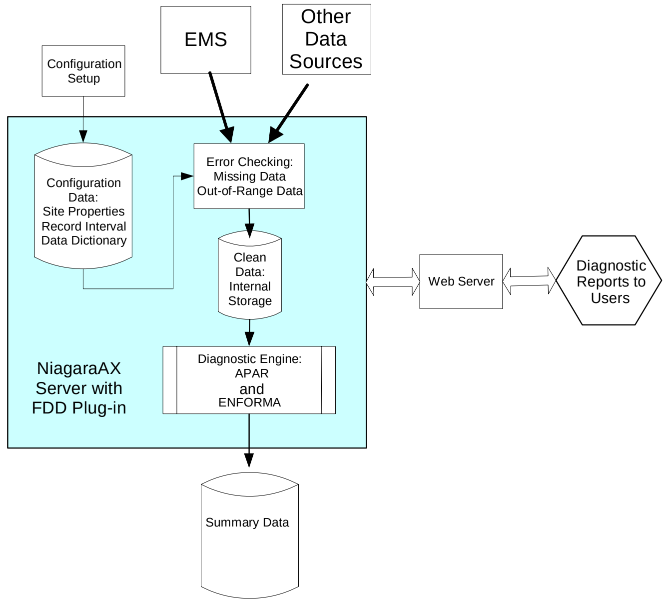
Figure 1: Remote Architecture



The remote architecture approach requires a reliable internet connection to the AX JACE. If possible, a local architecture may be used on one of the beta test sites. In the local architecture, shown in

Figure 2, a Niagara AX server with the FDD plug-in can be substituted for the AX JACE. The FDD engine runs as a plug-in to the local AX server.

Figure 2: Local Architecture



To provide the greatest benefit to California, the integrated diagnostic engine developed in this project will be available to any ASP who wishes to incorporate it into its offering. To facilitate licensing this capability to third parties, data transfer interfaces will be developed using XML over HTTP. XML over HTTP uses URIs with specific name/value pairs to invoke methods and processes within the Web Services framework. Once the URI is processed, a well-formatted XML document is returned as a response. To allow quick adoption, we may also provide simple XSLT service to parse the XML and convert it to an HTML document. The advantages of this approach are well understood by software developers, providing easier maintenance and development for both the ASP and diagnostic engine provider.

Each service provider will have their own on-site data collection equipment. This data is transferred to the ASP servers at least daily. Next, the data is transferred to the diagnostic web server for analysis. The results of this analysis are returned to the ASP, and then made available to the users via the World Wide Web in the form of reports or notifications.

During field testing, the fault detection routines will be subjected to conditions and systems that may not have been considered during testing with static sample data sets. Evaluating the effectiveness of the fault detection routines under new conditions will establish the robustness of the technique. Changes will be made, as necessary, to the routines to improve their performance.

To confirm the accuracy of the fault detection routines, data from each system will be evaluated both manually through trend log analysis, and automatically by the FDD engine. The purpose of the manual evaluation is to determine if faults exist that the FDD engine is missing, and conversely, to determine if the FDD engine is creating "false positives," i.e., the system is operating properly, but faults are being reported.

Any required changes to the FDD engine will first be developed and tested using Matlab, and then implemented in the production version of the FDD engine.

Similarly, any necessary changes to the user interface will be developed offline and then moved to the FDD server.

Typically, the installation of FDD will require the services of a Tridium Systems Integrator. For the sites in Colorado, we will be using the services of Western Building Services. WBS is a Staefa Talon dealer (Tridium OEM) and systems integrator. They have service contracts at several buildings and are interested in FDD to identify problems in their client's buildings. The California sites will use Systems Mechanical Inc., located in Richmond, CA, as much as possible for installation and system integration. Interviews with these systems integrators will provide a basis for verifying that installation issues are adequately addressed.

There are four objectives associated with the installation evaluation. They are:

1. Software Installation.

   For the alpha sites, no software will be installed onsite, as all processing will be performed on a server located at Architectural Energy Corporation. For any sites without an internet connection, software installation will be required.

2. Hardware.

   All sites that do not currently have a server running the NiagaraAX software will require additional hardware. For the remote installation architecture, a JACE will be installed and integrated with the existing hardware.

3. Integration issues.

   When FDD is added to a system that does not already have NiagaraAX installed, the existing and AX systems need to be integrated. Integration between NiagaraAX and other control systems is one of the reasons that it was selected as the deployment platform for FDD. Although integration is necessary whenever NiagaraAX is added to an existing system, and could be considered outside the scope of these field tests, there will be cases when NiagaraAX is added solely to provide fault detection capabilities.

   If FDD installation is relatively straightforward, market acceptance will be enhanced.

4. User response.

   Since fault detection, by itself, does not improve system performance, user response is critical. The users of the software must resolve the identified faults to achieve any energy savings. Therefore, evaluating user acceptance of the software is critical to achieving the goals of improved system performance and reduced energy consumption. User acceptance will be evaluated largely through interviews with personnel responsible for system operation, and personnel such as building owners and others with a financial stake in proper system operation.

2.4 Project Outcomes

2.4.1 User Interface

The ENFORMA Building Diagnostics user interface is viewed through a standard browser. A java applet is downloaded the first time the site is accessed. The UI design philosophy utilizes a series of tabs that allow the user to navigate through the various activities associated with using the FDD application. The activities performed through the UI include configuration of the FDD tool and viewing the results.

This section describes each of the FDD activities, their associated screens, and how the user interacts with the system. It does not discuss installation of the software or setting up the data histories, which would both be performed by the Systems Integrator.

2.4.2 Configuration Activities

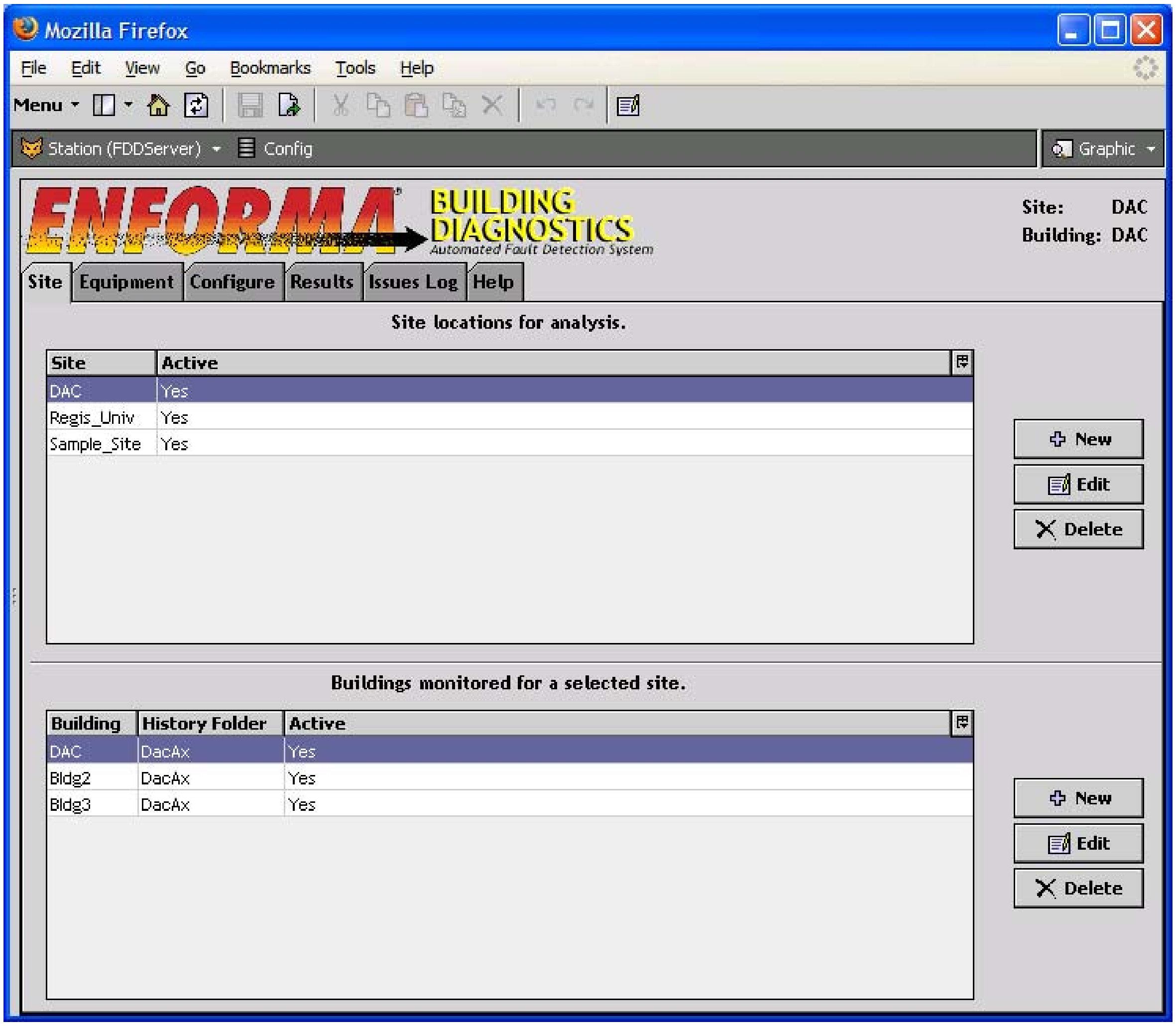
After histories for the required data points have been set up, the software must be configured so that it will access the data histories and report system faults. Configuring the FDD tool involves defining a site, the number and names of buildings at each site, and the number, type, and names of HVAC equipment located in each building.

2.4.2.1 Site Tab

Figure 3 shows the Site tab, which lists each site and the buildings at each site. Buildings and sites are added, renamed, or deleted from this view.

Once sites and buildings have been defined, this tab is also used to select the specific site and building to be viewed in subsequent tabs.

Figure 3: Site Screen



2.4.2.2 Equipment Tab

The equipment tab (Figure 4) is used to define equipment and associate data histories with each selected system.

The activities in the equipment tab include adding equipment and associating data histories with the measures required to perform the automated fault detection. The histories, which must be pre-defined, are associated with the measures by selecting each measure and clicking the "Edit" button, which then displays the Edit Measure dialog, shown in

Figure 5. The appropriate History Archive is selected from the dropdown list shown in the Edit Measure dialog.

Figure 4: Equipment Definition Screen

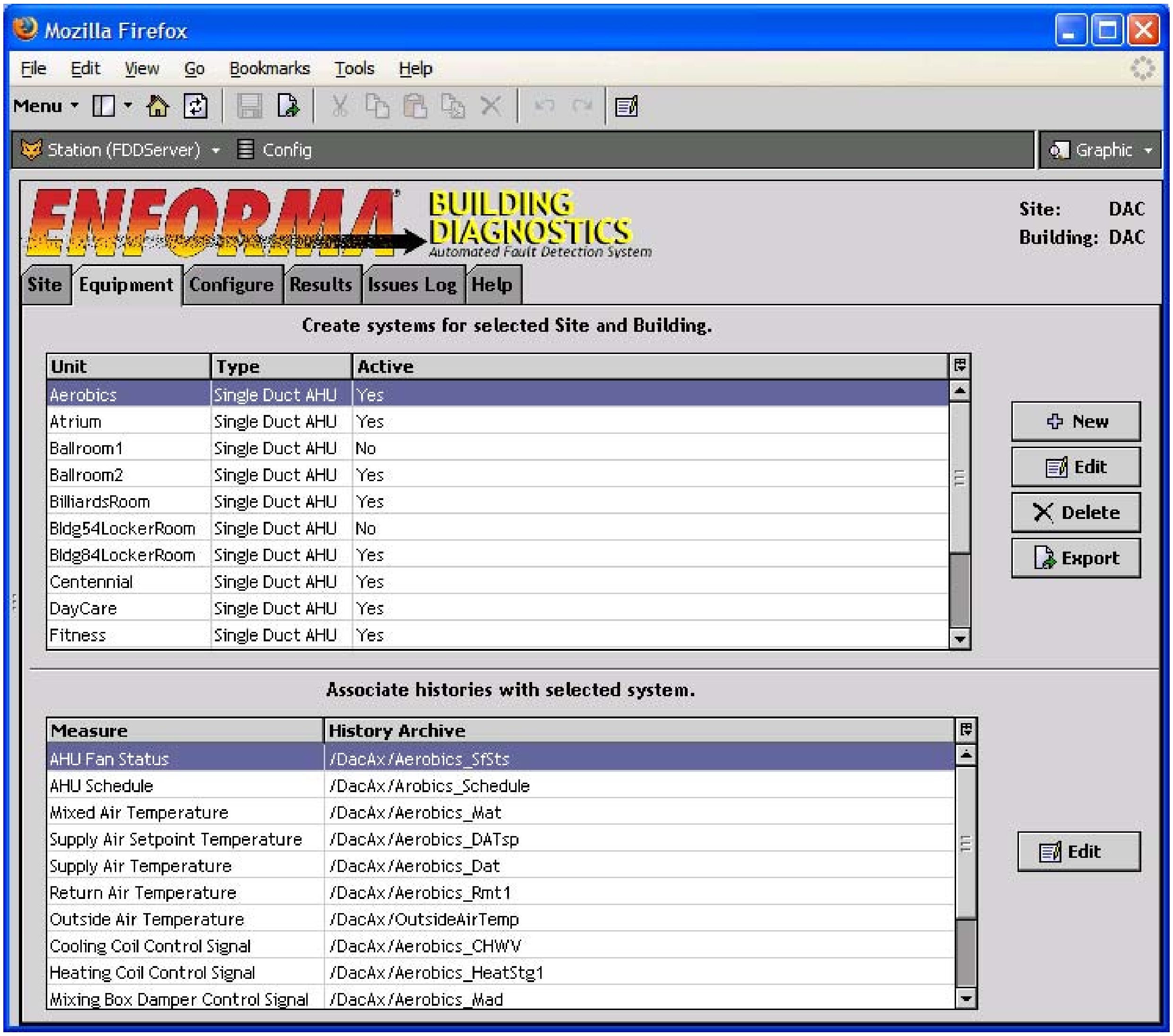
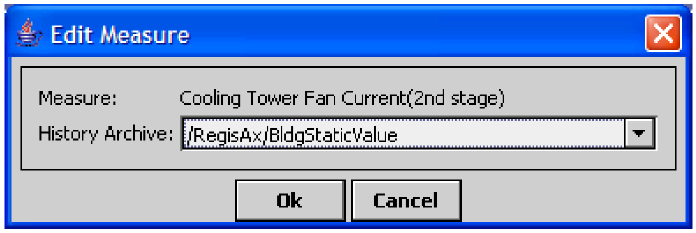


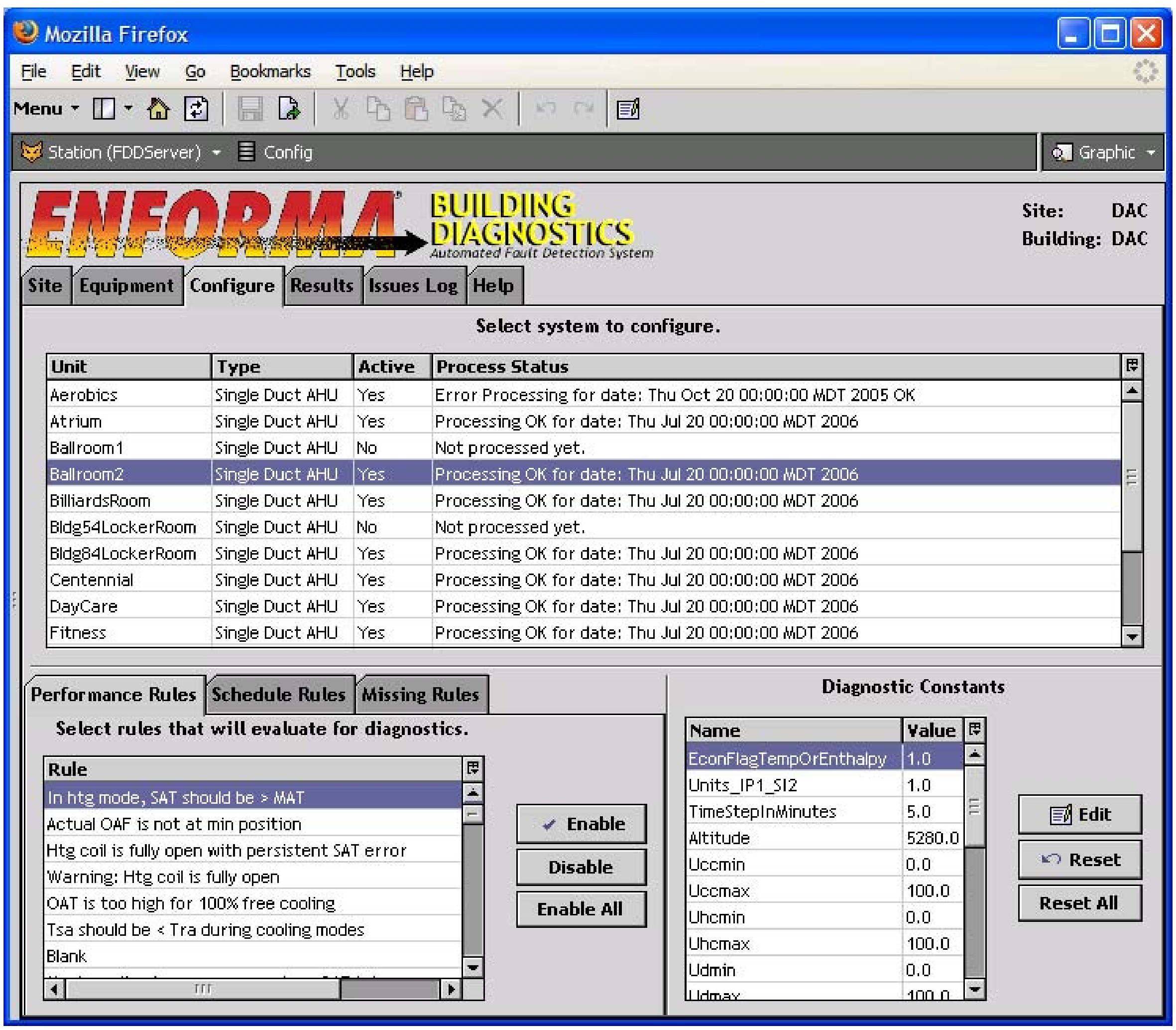
Figure 5: Map History with Required Measure



2.4.2.3 Configure Tab

Configuring the FDD tool for each piece of equipment is performed under the Configure tab (Figure 6). These activities include enabling and disabling rules as necessary, and setting the Diagnostic Constants. Although the capability exists to disable rules, in general, it is best to keep all rules enabled.

Figure 6: Configure Screen



2.4.2.4 Weekly Snapshot

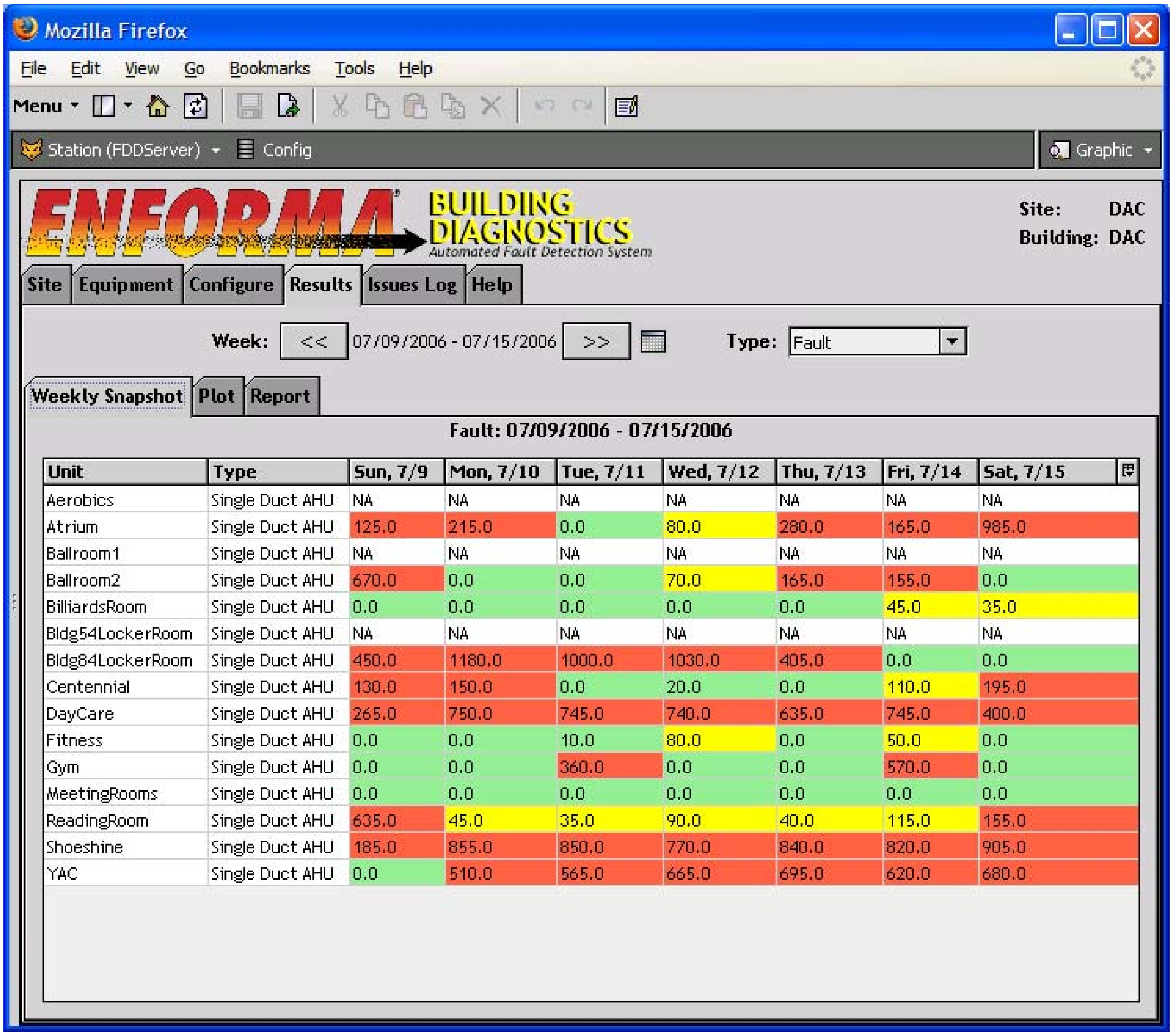
Viewing and interpreting a large amount of information in a single glance is one of the goals of the Snapshot view, which provides a color-coded representation of the condition of each system being evaluated. Green indicates that the system is ok, whereas yellow and red indicate potential problems at increasing thresholds.

There are several "Types" of snapshots available: Fault, Schedule, and Data Availability. The Fault snapshot displays the degree of faulty operation for each component in terms of fault-minutes, where a fault-minute is the sum of the duration of each fault encountered during the day. Multiple faults can occur at once, so it is possible to for the fault-minute sum to be greater than the period that the unit actually ran during the day.

The Schedule snapshot shows the number of minutes that the system was not operating in accordance with the BAS or baseline schedule.

The Data snapshot lists the sum of the minutes that each of the required data histories were missing. For example, if one data history was missing for an entire day, the value would be 1440. If four histories were missing for six hours, the value would also be 1440, and so forth.

Figure 7: Snapshot View



Unit	Type	Sun, 7/9	Mon, 7/10	Tue, 7/11	Wed, 7/12	Thu, 7/13	Fri, 7/14	Sat, 7/15
Aerobics	Single Duct AHU	NA	NA	NA	NA	NA	NA	NA
Atrium	Single Duct AHU	125.0	215.0	0.0	80.0	280.0	165.0	985.0
Ballroom1	Single Duct AHU	NA	NA	NA	NA	NA	NA	NA
Ballroom2	Single Duct AHU	670.0	0.0	0.0	70.0	165.0	155.0	0.0
BilliardsRoom	Single Duct AHU	0.0	0.0	0.0	0.0	0.0	45.0	35.0
Bldg54LockerRoom	Single Duct AHU	NA	NA	NA	NA	NA	NA	NA
Bldg84LockerRoom	Single Duct AHU	450.0	1180.0	1000.0	1030.0	405.0	0.0	0.0
Centennial	Single Duct AHU	130.0	150.0	0.0	20.0	0.0	110.0	195.0
DayCare	Single Duct AHU	265.0	750.0	745.0	740.0	635.0	745.0	400.0
Fitness	Single Duct AHU	0.0	0.0	10.0	80.0	0.0	50.0	0.0
Gym	Single Duct AHU	0.0	0.0	360.0	0.0	0.0	570.0	0.0
MeetingRooms	Single Duct AHU	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ReadingRoom	Single Duct AHU	635.0	45.0	35.0	90.0	40.0	115.0	155.0
Shoeshine	Single Duct AHU	185.0	855.0	850.0	770.0	840.0	820.0	905.0
YAC	Single Duct AHU	0.0	510.0	565.0	665.0	695.0	620.0	680.0

When the Results tab is first displayed, it shows the results for the current week. If desired, the forward and back buttons on each side of the date can scroll the view back or forward by one week. Alternately, the calendar button can be clicked which will display a calendar. Select the desired week to choose another period for viewing. When done with the calendar, it may be closed.

The snapshot view provides an overview of the health of each system evaluated by the FDD tool. However, it does not provide specific information about the faults that were detected. To learn more about the results for a specific system, cells can be highlighted by clicking on them. To view the results for multiple days, click on the first cell of interest and then drag to later days. Once the mouse button has been released, the selected cells will be highlighted, and the labels for the Plot and Report tabs will change from black to red, to indicate that details are available under those tabs.

2.4.2.5 Report Tab

The report tab will display hourly results or a daily summary, depending on whether a single day has been selected in the snapshot view, or multiple days have been selected, respectively. Figure 8 shows the hourly view. This lists the hour that the fault was detected, the mode, the number of minutes that the fault existed, and finally a description of the fault. The hourly view is useful since it indicates during which hour a fault occurred, but it can be rather lengthy if many different faults occurred during a day.

Both the hourly and daily summary views have an "Add Issue" button which displays the Add Issue dialog (Figure 8).

Figure 8: Report Rab – Hourly View.

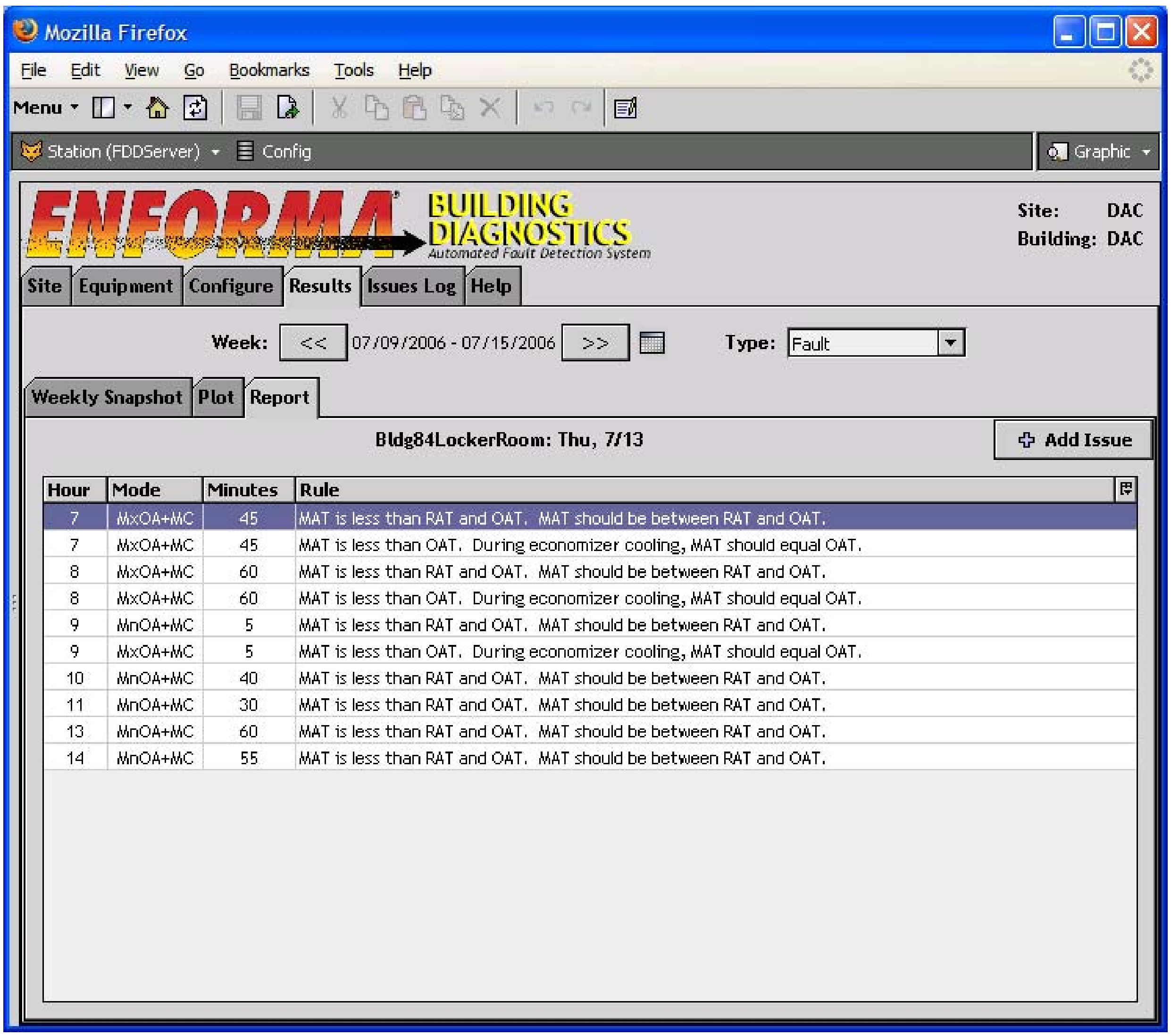
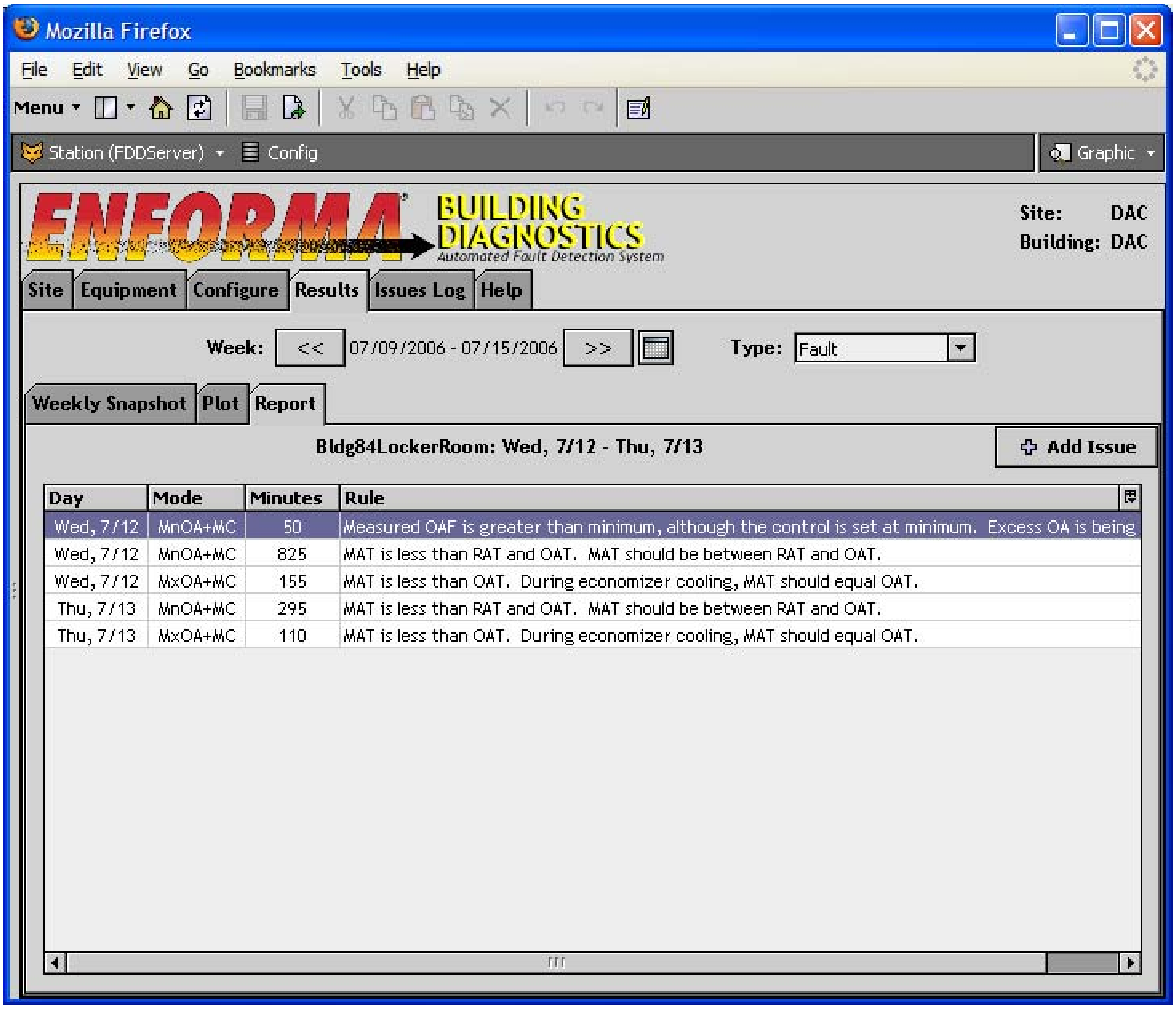


Figure 9 shows the daily view. This lists the date that the fault was detected, the mode, the number of minutes that the fault existed during the day, and finally a description of the fault. It provides a compact summary of the faults. This is often more readable than the hourly view, but of course does not provide indication of when during each day the faults actually happened.

Figure 9: Report Tab - Daily View.



2.4.2.6 Plot Tab

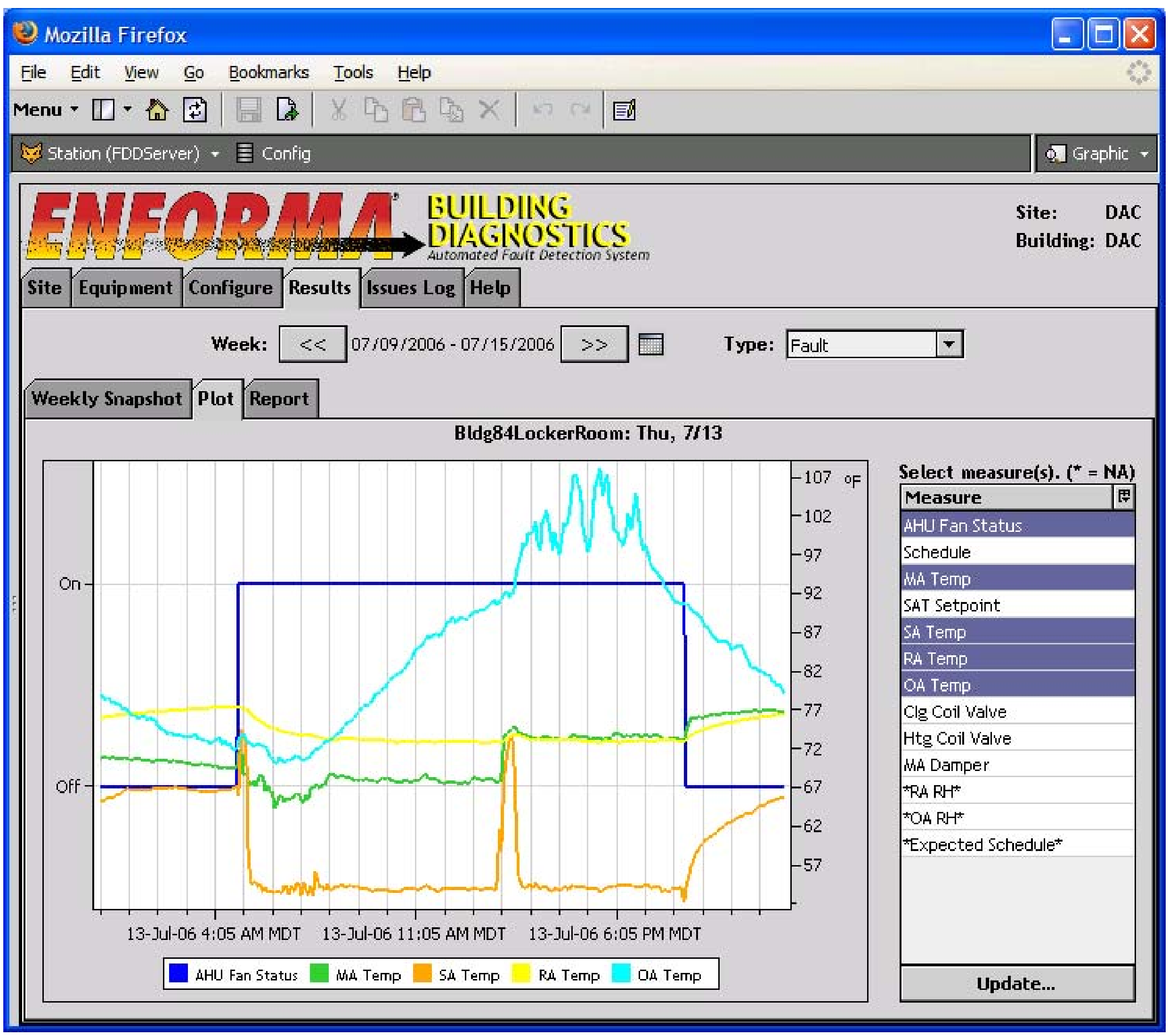
The plot tab (Figure 10) provides a method of viewing the data to confirm the results provided in the snapshot and report tabs.

One or more points can be selected in the list on the right-hand side of the screen. To select multiple data points, hold the "control" key down while clicking on the desired points. Once the points have been selected, click on "Update…" to refresh the plot. If a point has not been associated with a history, there is no data to plot. Asterisks indicate which points have not been associated with histories.

Each system type has a set of default points that will be plotted when initially viewing the plot tab. This set of points can be modified, as described above. When the plot tab is exited, the selection of points is saved so that the next time the plot tab is selected, the new set of points is plotted. This allows custom plots for each system. For example, if one air handler is having problems with interaction between the control valves and dampers, the engineer might plot HW and CHW valve position, damper position, and fan status. Similarly, another air handler might be having sensor calibration issues. On this system it would be appropriate to plot the fan status and the suspect sensors. In both cases, the fan status was selected so that it was clear when the system was actually operating.

The plotting tool included within the Niagara framework allows zooming and panning through mouse clicks. The plot can be zoomed by clicking and dragging the mouse cursor. Once the plot has been zoomed, a control is displayed that allows panning in the zoomed axis, or returning to the original scale.

Figure 10: Plot Tab



2.4.2.6 Issues Log

Actions taken to resolve problems within the HVAC systems identified by the FDD tool should be recorded. The Issues Log is where these actions can be recorded within the FDD environment. Figure 11 shows the Issues Log view. This view consists of a list of the systems with the number of issues entered for each unit, and a list of the issues displayed for the highlighted unit.

Figure 11: Issues Log Tab.

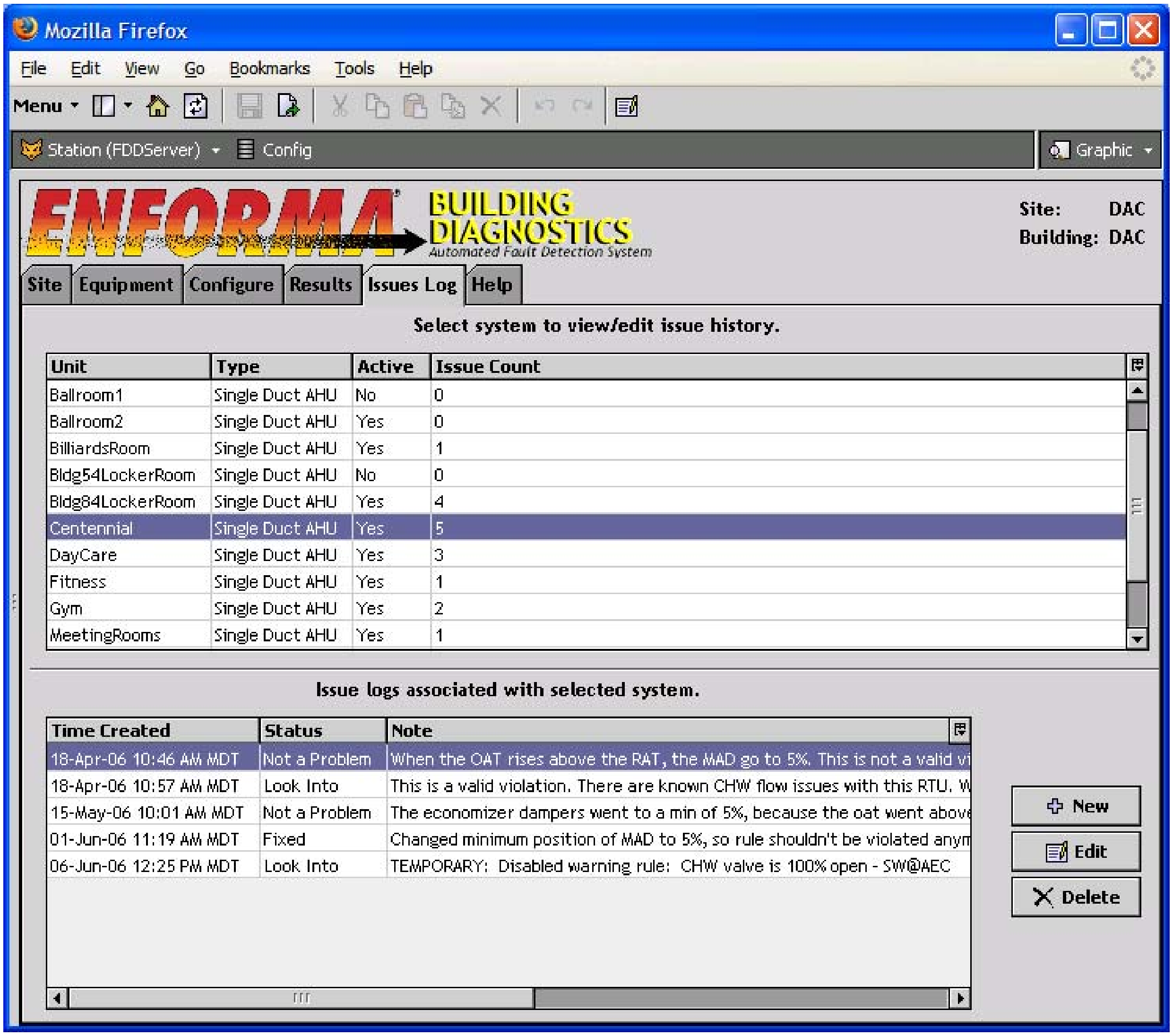
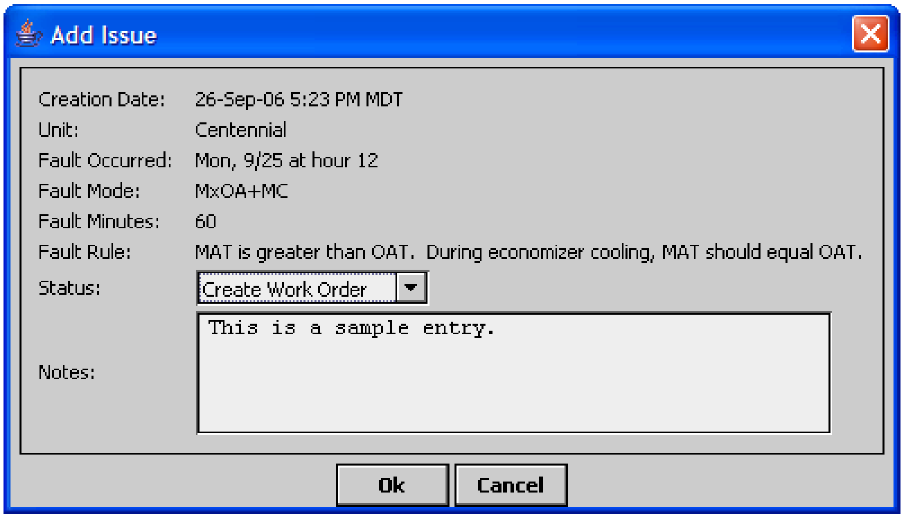


Figure 12 shows the Add Issue dialog. This is displayed when the "Add Issue" button is clicked in the report displays, as discussed earlier, or when "New" or "Edit" is clicked in the Issues Log view.

Figure 12: Add Issue Dialog



When the Add Issue dialog is opened from one of the report views, the time that the fault occurred, the mode, and the duration of the fault are displayed. If the Add Issue dialog is opened when viewing hourly results, it will list the time of the fault on an hourly basis, as shown in
Figure 12. If viewing daily results, it will list the date of the fault, but not list the hour of the fault.

If an issue is added from the Issues Log view, the fields associated with identifying the fault time, type, and duration will be blank.

2.5 Conclusions and Recommendations

The ENFORMA Building Diagnostics (EBD) project has accomplished its goals and can be considered a success for several reasons:

1. EBD has successfully implemented and extended the APAR rule set as a java module that runs within the NiagaraAX environment.
2. EBD has been deployed into a range of buildings, and has provided useful information that can lead to improving the performance of HVAC equipment.
3. California DGS has plans to deploy EBD in additional buildings, beyond the initial DGS Resources building. Additional deployment is a result of the successes at Resources in identifying existing problems, and providing monetary incentive to fix the problems.
4. Commercial interest is continuing to grow.

It is because of these reasons that EBD development is continuing beyond the completion of this project.

CHAPTER 3:
Project 3: AHU and VAV Diagnostics

3.1 Introduction

Building HVAC equipment routinely fails to satisfy performance expectations envisioned at design. Such failures often go unnoticed for extended periods of time. Additionally, higher expectations are being placed on a combination of different and often conflicting performance measures, such as energy efficiency, indoor air quality, comfort, reliability, limiting peak demand on utilities, etc. To meet these expectations, the processes, systems, and equipment used in both commercial and residential buildings are becoming increasingly sophisticated. This development both necessitates the use of automated diagnostics to ensure fault-free operation and enables diagnostic capabilities for the various building systems by providing a distributed platform that is powerful and flexible enough to perform fault detection and diagnostics (FDD).

Most of today's emerging FDD tools are stand-alone software products that do not reside in a building control system. Thus, trend data files must be processed off-line, or an interface to the building control system must be developed to enable on-line analysis. This does not scale well because all of the data must be obtained at a single point. A better solution is to embed FDD in the local controller for each piece of equipment, so that the FDD algorithm is executed as a component of the control logic. NIST has developed FDD methods that can detect common mechanical faults and control errors in air-handling units (AHUs) and variable-air-volume (VAV) boxes. The tools are sufficiently simple that they can be embedded in commercial building control systems and only rely upon sensor data and control signals that are commonly available in commercial building automation and control systems.

In previous research, software tools have been developed to implement APAR and VPACC, then tested and refined using data generated by simulation, emulation, and laboratory testing [1] and data collected from real buildings [2]. APAR and VPACC have also been embedded in commercial AHU and VAV box controllers from several manufacturers and tested in emulation and laboratory environments [3].

The project described in this report was designed to move the FDD algorithms from the research environment to commercial HVAC control products. Several methods to communicate the results of the FDD calculations to the system operator were developed. Robust FDD parameters for both APAR and VPACC were developed to eliminate the need for site-specific configuration. APAR and VPACC were embedded in commercial AHU and VAV box controllers for a multiple site field demonstration which was conducted to establish confidence in automated diagnostics and to familiarize potential vendors and users with FDD.

3.2 Project Objectives

Remove the remaining barriers to commercializing APAR and VPACC (the automated AHU and VAV Box FDD tools developed by NIST).

By involving the controls manufacturers directly in the field tests, the reliability and effectiveness of the FDD tools will be demonstrated, increasing confidence in this technique. The current embedded versions of the tools are written using generic mathematical functions available in the languages in which the controllers are programmed. Although this approach is suitable for a technology demonstration, built-in FDD functions would greatly simplify the task of embedding diagnostics in the control programs for AHUs and VAV boxes, and is therefore necessary for their widespread commercial use. By giving the manufacturers hands-on experience with FDD it will encourage the manufacturers to develop such built-in functions. NIST will use the data from these field tests to develop sets of robust parameters to be used for the FDD algorithms, as well as the criteria to determine when each set should be used, so they can be used without the collection and analysis of trend data from each potential installation.

One or more HVAC controls manufacturer will offer automated diagnostics in its AHU and VAV box controller products as a result of this project.

Competitive pressure will then give the other manufacturers a powerful incentive to provide their products with similar capabilities. NIST has ongoing partnerships with Alerton, Automated Logic, and Delta Controls, and is currently in discussions with Siemens Building Technologies. These firms are all well established in the market. Their products are widely distributed across the U.S. and overseas. In addition, these partners have provided hardware, software, and technical support to NIST to support control systems research, indicating a commitment to advancing the state of the art, as well as reducing the threshold for technological buy-in. Furthermore, the controls manufacturers have access, either at their headquarters facilities or through their local representatives, to a wide variety of sites for the field tests. Securing the commitment of one or more of these potential partners to commercialize AHU and VAV box diagnostics is critical to the success of the proposed project. NIST has secured verbal commitments from all four manufacturers, and is currently working out the details of a written agreement.

3.3 Project Approach

3.3.1 AHU Performance Assessment Rules (APAR)

The basis for the air handling unit fault detection methodology is a set of expert rules used to assess the performance of the AHU. The tool developed from these rules is APAR (AHU Performance Assessment Rules). A brief overview of APAR is presented here.

APAR is applicable to single duct VAV and constant volume AHUs with airside economizers. The operation of this type of AHU during occupied periods can be classified into a number of modes, depending on the heating/cooling load and outdoor air conditions. Each mode of operation can be characterized by a different range of values for each of three control signals:

the heating coil valve, cooling coil valve, and mixing box dampers. For convenience, the operating modes are summarized below:

Mode 1: heating

Mode 2: cooling with outdoor air

Mode 3: mechanical cooling with 100 % outdoor air

Mode 4: mechanical cooling with minimum outdoor air

Mode 5: unknown

Once the mode of operation has been established, rules based on conservation of mass and energy can be evaluated using the sensor and control signal information that is typically available from AHUs. APAR has a total of 28 rules (Table 1). Each rule is expressed as a logical statement that, if true, indicates the presence of a fault. Because the mass and energy balances are different for each mode of operation, a different subset of the rules applies to each mode. There are also some rules that are independent of the operating mode and are always evaluated. A list of possible causes is associated with each rule (Table 2).

Several modifications to the basic APAR algorithm were made to enhance usability and reduce nuisance alarms. Each rule can be individually disabled by the user in order to eliminate nuisance alarms caused by fault conditions that are known to the maintenance staff, but will not be repaired immediately. Since the rules are based on steady state assumptions, there are several delays, during which the rules are not evaluated, to ensure that quasi-steady state conditions exist. There is a delay at the beginning of occupancy and another delay after each mode switch. A third delay establishes the length of time a rule must be satisfied before an alarm is reported. Furthermore, the rules are evaluated using exponentially weighted moving averages of the raw data rather than the current values.

The rules in Table 1 are generic, not tightly linked to a specific sequence of operations. The rule set was developed for AHUs with hydronic heating and cooling coils and relative enthalpy-based economizers, however, it can easily be adapted for different types of AHUs. For example, Rules 9 and 15 will change based on the type of economizer, whether it is temperature- or enthalpy-based, and whether it compares outdoor conditions to return or to a fixed changeover condition, or some combination thereof. If the cooling coil uses direct expansion instead of chilled water, Rules 13, 14, 19, and 20 do not apply. Also, the causes in Table 2 related to the cooling coil valve (valve stuck or leaking) or the chilled water system (chilled water supply temperature too high, problem with chilled water circulating pump, chilled water not available) are interpreted as problems with the mechanical refrigeration system. If some form of staged heating (electric or combustion) is used instead of hydronic heating, Rules 3 and 4 do not apply. Also, the causes in Table 1 related to the heating coil valve (valve stuck or leaking) or the hot water system (hot water supply temperature too low, problem with hot water circulating pump) are interpreted as problems with the staged heating system. For single zone or other AHUs with no supply air temperature setpoint, Rules 5, 8, 13, 19, and 25 do not apply. If there is no mixed air temperature sensor, delete Rules 1, 2, 7, 10, 11, 16, 18, 26, and 27 cannot be evaluated and therefore do not apply.

Table 1: APAR Rule Set

Mode	**Rule #**	**Rule Expression** (true implies existence of a fault)
Heating **(Mode 1)**	1	$T_{sa} < T_{ma} + \Delta T_{sf} - \varepsilon_t$
	2	For $\lvert T_{ra} - T_{oa} \rvert \geq \Delta T_{min}$: $\lvert Q_{oa}/Q_{sa} - (Q_{oa}/Q_{sa})_{min} \rvert > \varepsilon_f$
	3	$\lvert u_{hc} - 1 \rvert \leq \varepsilon_{hc}$ and $T_{sa,s} - T_{sa} \geq \varepsilon_t$
	4	$\lvert u_{hc} - 1 \rvert \leq \varepsilon_{hc}$
Cooling with Outdoor Air **(Mode 2)**	5	$T_{oa} > T_{sa,s} - \Delta T_{sf} + \varepsilon_t$
	6	$T_{sa} > T_{ra} - \Delta T_{rf} + \varepsilon_t$
	7	$\lvert T_{sa} - \Delta T_{sf} - T_{ma} \rvert > \varepsilon_t$
Mechanical Cooling with 100% Outdoor Air **(Mode 3)**	8	$T_{oa} < T_{sa,s} - \Delta T_{sf} - \varepsilon_t$
	9	$T_{oa} > T_{co} + \varepsilon_t$
	10	$\lvert T_{oa} - T_{ma} \rvert > \varepsilon_t$
	11	$T_{sa} > T_{ma} + \Delta T_{sf} + \varepsilon_t$
	12	$T_{sa} > T_{ra} - \Delta T_{rf} + \varepsilon_t$
	13	$\lvert u_{cc} - 1 \rvert \leq \varepsilon_{cc}$ and $T_{sa} - T_{sa,s} \geq \varepsilon_t$
	14	$\lvert u_{cc} - 1 \rvert \leq \varepsilon_{cc}$
Mechanical Cooling with Minimum Outdoor Air **(Mode 4)**	15	$T_{oa} < T_{co} - \varepsilon_t$
	16	$T_{sa} > T_{ma} + \Delta T_{sf} + \varepsilon_t$
	17	$T_{sa} > T_{ra} - \Delta T_{rf} + \varepsilon_t$
	18	For $\lvert T_{ra} - T_{oa} \rvert \geq \Delta T_{min}$: $\lvert Q_{oa}/Q_{sa} - (Q_{oa}/Q_{sa})_{min} \rvert > \varepsilon_f$
	19	$\lvert u_{cc} - 1 \rvert \leq \varepsilon_{cc}$ and $T_{sa} - T_{sa,s} \geq \varepsilon_t$
	20	$\lvert u_{cc} - 1 \rvert \leq \varepsilon_{cc}$
Unknown Occupied Modes **(Mode 5)**	21	$u_{cc} > \varepsilon_{cc}$ and $u_{hc} > \varepsilon_{hc}$ and $\varepsilon_d < u_d < 1 - \varepsilon_d$
	22	$u_{hc} > \varepsilon_{hc}$ and $u_{cc} > \varepsilon_{cc}$
	23	$u_{hc} > \varepsilon_{hc}$ and $u_d > \varepsilon_d$
	24	$\varepsilon_d < u_d < 1 - \varepsilon_d$ and $u_{cc} > \varepsilon_{cc}$
All Occupied Modes **(Mode 1, 2, 3, 4, or 5)**	25	$\lvert T_{sa} - T_{sa,s} \rvert > \varepsilon_t$
	26	$T_{ma} < min(T_{ra}, T_{oa}) - \varepsilon_t$
	27	$T_{ma} > max(T_{ra}, T_{oa}) + \varepsilon_t$
	28	Number of mode transitions per hour $> MT_{max}$

Where

MT_{max} = maximum number of mode changes per hour

T_{sa} = supply air temperature

T_{ma} = mixed air temperature

T_{ra} = return air temperature

T_{oa} = outdoor air temperature

T_{co} = changeover air temperature for switching between Modes 3 and 4

$T_{sa,s}$ = supply air temperature setpoint

ΔT_{sf} = temperature rise across the supply fan

ΔT_{rf} = temperature rise across the return fan

ΔT_{min} = threshold on the minimum temperature difference between the return and outdoor air

Q_{oa}/Q_{sa} = outdoor air fraction = $(T_{ma} - T_{ra})/(T_{oa} - T_{ra})$

$(Q_{oa}/Q_{sa})_{min}$ = threshold on the minimum outdoor air fraction

u_{hc} = normalized heating coil valve control signal [0,1] where $u_{hc} = 0$ indicates the valve is closed and $u_{hc} = 1$ indicates it is 100 % open

u_{cc} = normalized cooling coil valve control signal [0,1] where $u_{cc} = 0$ indicates the valve is closed and $u_{cc} = 1$ indicates it is 100 % open

u_d = normalized mixing box damper control signal [0,1] where $u_d = 0$ indicates the outdoor air damper is closed and $u_d = 1$ indicates it is 100 % open

ε_t = threshold for errors in temperature measurements

ε_f = threshold parameter accounting for errors related to airflows (function of uncertainties in temperature measurements)

ε_{hc} = threshold parameter for the heating coil valve control signal

ε_{cc} = threshold parameter for the cooling coil valve control signal

ε_d = threshold parameter for the mixing box damper control signal

Table 2: VPACC Diagnoses

Rule #	Alarm Description	Supply Air Temperature Sensor Error	Return Air Temperature Sensor Error	Mixed Air Temperature Sensor Error	Outdoor Air Temperature Sensor Error	Leaking Cooling Coil Valve	Stuck Cooling Coil Valve	Undersized Cooling Coil	Fouled Cooling Coil	Chilled Water Supply Temperature Too High	Problem with Chilled Water Circulating Pump	Chilled Water not Available to Season	Leaking Heating Coil Valve	Stuck Heating Coil Valve	Undersized Heating Coil	Fouled Heating Coil	Hot Water Supply Temperature Too Low	Problem with Hot Water Circulating Pump	Leaking Mixing Box Damper	Stuck Mixing Box Damper
		Possible Diagnoses																		
1	In heating mode, supply air temp should be greater than mixed air temp.	X		X		X	X							X	X	X	X	X		
2	Outdoor air fraction (percentage of outdoor air) is too low or too high.		X	X	X														X	X
3	Heating coil valve command is fully open and supply air temp error exists.	X				X	X							X	X	X	X	X		
4	Heating coil valve command is fully open. If heating load increases, supply air temp will drift from setpoint.	X				X	X							X	X	X	X	X		
5	Outdoor air temp is too warm for cooling with outdoor air.	X			X															
6	Supply air temp should be less than return air temp.	X	X										X	X						
7	Supply and mixed air temp should be nearly the same.	X		X		X	X						X	X						
8	Outdoor air temperature is too cool for mechanical cooling with 100% outdoor air.	X			X								X	X					X	X
9	Outdoor air enthalpy is too great for mechanical cooling with 100% outdoor air.																			
10	Outdoor and mixed air temp should be nearly the same.			X	X														X	X
11	Supply air temp should be less than mixed air temp.	X		X			X	X	X	X	X	X	X	X						
12	Supply air temp should be less than return air temp.	X	X				X	X	X	X	X	X	X	X						
13	Cooling coil valve command is fully open and supply air temp error exists.	X					X	X	X	X	X	X	X	X						
14	Cooling coil valve command is fully open. If cooling load increases, supply air temp will drift from setpoint.	X					X	X	X	X	X	X	X	X						
15	Outdoor air enthalpy is too low for mechanical cooling with minimum outdoor air.																			
16	Supply air temp should be less than mixed air temp.	X		X			X	X	X	X	X	X	X	X						
17	Supply air temp should be less than return air temp.	X	X				X	X	X	X	X	X	X	X						
18	Outdoor air fraction (percentage of outdoor air) is too low or too high.		X	X	X														X	X
19	Cooling coil valve command is fully open and supply air temp error exists.	X					X	X	X	X	X	X	X	X						
20	Cooling coil valve command is fully open. If cooling load increases, supply air temp will drift from setpoint.	X					X	X	X	X	X	X	X	X						
21	Heating coil valve, cooling coil valve, and mixing box dampers are all modulating simultaneously.																			
22	Heating coil valve and cooling coil valve are both modulating simultaneously.																			
23	Heating coil valve and mixing box dampers are both modulating simultaneously.																			
24	Cooling coil valve and mixing box dampers are both modulating simultaneously.																			
25	Persistent supply air temp error exists.																			
26	Mixed air temp should be between return and outdoor air temp (mixed air temp too great).		X	X	X															
27	Mixed air temp should be between return and outdoor air temp (mixed air temp too low).		X	X	X															
28	Too many mode switches per hour.																			

3.3.2 VAV Box Performance Assessment Control Charts - VPACC

The challenges presented in detecting and diagnosing faults in VAV boxes are similar to those encountered with other pieces of HVAC equipment. Generally there are very few sensors, making it difficult to determine what is happening in the device. Limitations associated with controller memory and communication capabilities further complicate the task. The number of different types of VAV boxes and lack of standardized control sequences add a final level of complexity to the challenge. These needs and constraints led to the development of VAV Box Performance Assessment Control Charts (VPACC), a fault detection tool that uses a small number of control charts to assess the performance of VAV boxes. A brief overview of VPACC is presented here.

VPACC implements an algorithm known as a CUSUM (cumulative sum) chart. The basic concept behind CUSUM charts is to accumulate the error between a process output and the expected value of the output. Large values of the accumulated error indicate an out of control process. Mathematically, the technique can be expressed as:

$$z_i = (x_i - x_{exp}) / \sigma_{exp}$$

where zi is the normalized error at time i, xi is the error at time i, xexp is the expected value of the error, and σexp is the expected variation of the error. Separate positive (S) and negative (T) sums are then accumulated. The slack parameter, k, is defined as the amount of variation that is considered normal, and therefore ignored. The cumulative positive and negative sums are calculated by:

$$S_i = max[0, z_i - k + S_{i-1}]$$

$$T_i = max[0, -z_i - k + T_{i-1}]$$

The final step is to compare *S* and *T* to the alarm limit, *h*, to determine whether the process is out of control.

In order to make VPACC independent of the control strategy used in a particular controller/VAV box application, four generic errors were identified: the airflow rate error, the absolute value of the airflow rate error, the temperature error, and the discharge air temperature error. As long as the VAV box controller has an airflow setpoint, as well as heating and cooling temperature setpoints, VPACC will function independently of the specific control strategy used. Common mechanical and control faults will result in a positive or negative deviation of one or more of these errors from its value during normal operation, which can be detected by a CUSUM chart. A list of possible causes is associated with each alarm (

Table 3: VPACC Alarm Diagnoses).

The airflow rate error, Q_{error}, is defined as the difference between the measured airflow rate and the airflow rate setpoint. The absolute value of the airflow rate error, $|Q_{error}|$, is defined simply as the absolute value of the difference between the measured airflow rate and the airflow rate setpoint. Only one CUSUM value is defined for this error since it is never negative.

The zone temperature error, T_{error}, is defined as

$$T_{error} = T_{zone} - CSP \quad : \text{ If } T_{zone} > CSP$$

$$T_{error} = 0 \quad : \text{ If } HSP \leq T_{zone} \leq CSP$$

$$T_{error} = T_{zone} - HSP \quad : \text{ If } T_{zone} < HSP$$

where

T_{zone} = zone temperature

CSP = cooling setpoint

HSP = heating setpoint.

The discharge air temperature error, DATerror, is only applied to VAV boxes with hydronic reheat. The DATerror is calculated only when the reheat coil valve is fully closed, otherwise it is set equal to zero. It is defined as the difference between the VAV box discharge air temperature and the entering air temperature. The supply air temperature from the AHU serving the VAV box can be used as a surrogate for the entering air temperature. This value is generally obtained via the building control network.

Table 3: VPACC Alarm Diagnoses

Alarm Description	Possible Diagnoses: Zone temperature sensor drift/failure	Airflow (DP) sensor drift/failure	Discharge temperature sensor drift/failure	Damper stuck or failed	Damper actuator stuck or failed	Reheat coil valve stuck or failed	Reheat coil valve actuator stuck or failed	AHU Supply air too warm	AHU Supply air too cool	Supply air static pressure too low	Scheduling conflict with AHU	Undersized VAV box	Tuning problem with airflow feedback control loop	Tuning problem with zone temperature feedback control loop	Inappropriate zone temperature setpoint	Minimum airflow setpoint too low	Minimum airflow setpoint too high	Maximum airflow setpoint too low	Maximum airflow setpoint too high	Sequencing logic error
High zone temperature alarm	X	X				X	X	X			X	X	X	X	X			X		X
Low zone temperature alarm	X	X				X	X		X		X	X	X	X	X		X			X
High airflow alarm		X		X	X						X		X							X
Low airflow alarm		X		X	X					X	X	X	X						X	X
Unstable airflow alarm		X		X	X					X	X	X	X			X				X
High discharge temperature alarm			X			X	X													
Low discharge temperature alarm			X			X	X													

The errors and CUSUMs are only calculated during occupied periods. During unoccupied periods, the errors are not computed and the CUSUMs are reset to zero. There is a delay at the onset of the occupied period to allow quasi-steady state conditions to develop. Also, the CUSUMs are periodically reset to zero to prevent alarms from being reported due to small steady state errors. Each alarm can be individually disabled by the user in order to eliminate nuisance alarms caused by fault conditions that are known to the maintenance staff, but will not be repaired immediately.

VPACC was developed for pressure independent VAV boxes with hydronic reheat coils, however, it can easily be adapted for different types of VAV boxes. For cooling only VAV boxes or boxes that do not have discharge air temperature sensors, the discharge air temperature error ($\Delta Terror$) does not apply. For dual duct boxes, two airflow errors ($Qerror,hot$ and $Qerror,cold$) and two absolute value airflow errors ($|Qerror, hot|$ and $|Qerror, cold|$) are needed, and the discharge air temperature error ($\Delta Terror$) does not apply. Although VPACC was originally tested using VAV boxes without fans [1, 2, 3, 5], the algorithm is independent of fan configuration and can be applied to boxes with series or parallel fans without modification.

3.3.2 FDD Interface

In addition to providing access to the data that the algorithms need and a platform to perform the calculations, the BAS also provides an interface between the results of the FDD algorithms and the operator. The results of APAR and VPACC consist, within the controller, of a set of fault conditions as shown in Table 1 and Table 2. There are several different ways to communicate the results to the operator.

3.3.2.1 Alarms

Most BASs provide some alarm or event handling capability. Each FDD fault condition can be configured as a BAS alarm point with the appropriate text message from Table 2 or

Table 3 When a rule is satisfied (APAR) or a CUSUM exceeds the alarm limit (VPACC), a BAS alarm is reported. There are various options for instantaneous notification via the operator workstation, printer, email, fax, or pager. Alarms are also logged in an alarm history file or database. If an alarm is investigated at the time it occurs, diagnosis and troubleshooting are aided by observation of the system during faulty operation. An alternative is to review the alarm history for each piece of equipment before performing scheduled maintenance. If any faults have been recorded since the previous maintenance, corrective action can be taken.

3.3.2.2 Work Orders

Facilities that use a computerized maintenance management system (CMMS) can have work orders generated automatically when faults are detected. Interfacing the CMMS with FDD is typically done by having the CMMS periodically query the AHU and VAV box controllers for fault status, then generate a work order for each device with one or more faults. The work order would identify the piece of equipment, the time and date the fault was detected, and include descriptive information about the fault(s) detected from Table 2 or

Table 3. Implementation requires some configuration of the CMMS to communicate with the AHU and VAV box controllers including drivers for the network communication protocol used by the BAS. The greater persistence and visibility of work orders compared to BAS alarms is the primary benefit of this approach, but it means that the potential harm caused by false alarms is also greater. In order to minimize the danger of false alarms, the building operator should have the capability of disabling the FDD-work order process when certain conditions exist that are likely to cause false alarms. There should also be a provision to delete erroneous work orders.

3.3.2.3 Fault Codes

Rather than reporting faults as BAS alarms or work orders, trend logs could be used to monitor the equipment fault status. To reduce the number of trend logs, several binary fault statuses for a particular piece of equipment could be combined using a bitmask into a single analog fault code. This approach can be useful as a service tool. It could also be used in an initial installation of FDD to verify its performance before enabling the generation of alarms or work orders.

3.3.2.4 Robust FDD Parameters

There are a wide variety of disturbances that can cause an HVAC system to deviate from ideal, "normal operation" conditions, but are not actual faults and should not be reported as such. These include variations in outdoor temperature, wind velocity and direction, solar radiation, internal heat sources, and changes in system mode of operation or schedule. Normal non-idealities of the HVAC system, such as minor sensor drift, errors due to analog-to-digital or digital-to-analog converter resolution, electronic noise, small deviations from setpoint, actuator hysteresis, etc., also should not be reported as faults. Many FDD methods, including APAR and VPACC, employ a set of parameters that collectively define the severity of a fault needed in order to report an alarm. If the cutoff severity needed to trigger an alarm is too great, real faults will remain undetected (false negatives). However, if the cutoff severity is too small, false alarms (false positives) will be generated. FDD parameters must be selected carefully to minimize both false positives and false negatives.

In previous research, the FDD parameters for APAR and VPACC were determined on a site-specific basis. For each data source, whether it was a simulation, emulation, laboratory, or field test site, initial guess values of the parameters were refined through trial and error [1, 2, 3, 5, 6]. It is expected that for most control system integrators and building owners, the need to develop a site-specific set of parameters presents a major barrier to the adoption of FDD, both in terms of a detailed understanding of the APAR and VPACC algorithms as well as the time and resources required. To overcome this obstacle, a set of robust FDD parameters was developed. These parameters were found to be effective for a variety of mechanical system types, building uses, and weather conditions based on application to previous work as well as to multiple test sites in a field demonstration of APAR and VPACC concurrent with the study described in this report.

In the development of any set of FDD parameters, there is an inherent tradeoff between false negatives (real faults remain undetected) and false positives (false alarms). For the tabulated set of parameters, this tradeoff is biased toward minimizing false alarms, if necessary at the expense of missing some real faults. Most facilities have limited manpower available to follow up on reported faults, so by reporting only relatively severe faults, technician productivity is maximized as repairs are made to the most serious problems. Minimizing false alarms is crucial since too many false alarms will cause O&M staff to waste time and lose confidence in the FDD algorithms, ultimately causing real faults to be ignored. Furthermore, a large number of fault reports, whether real or false, may be more information than the O&M staff can process.

3.3.2.5 Tuning FDD Parameters for Optimum Performance

In most cases it is expected that the tabulated FDD parameters will be used. However, some building operators may need to develop their own parameter values. For example, a particular facility may find that, although the faults that are reported are legitimate, there are too many for the operations and maintenance (O&M) staff to handle. In this case, the parameters will be adjusted so that the threshold severity for a fault to be reported is increased. Or, in a facility that has more resources available and is particularly interested in reducing energy consumption, the parameters might be adjusted so that the threshold severity is reduced. To enable users to make these adjustments, guidelines for tuning the FDD parameters are included.

3.3.2.6 Tuning APAR Parameters

Some of the parameters can be determined directly by evaluating the mechanical system. The values for supply and return fan temperature rise can be determined from design data or field measurements.

The minimum temperature difference for ventilation rules can be determined by evaluating trendlogs of the return, outdoor, and mixed air temperatures, and the mixing box damper control signal. For each logged data sample, the actual outdoor air fraction can be compared with the calculated outdoor air fraction based on the temperature data. Correlating the accuracy of the calculated outdoor air fraction with the difference between the return and outdoor air temperatures will yield the minimum temperature difference for ventilation rules.

The occupancy delay can be determined by evaluating trendlogs of the supply air temperature and setpoint. The occupancy delay parameter should be set equal to the time from the onset of the occupancy until the supply air temperature is reasonably close to the setpoint. Then a margin of safety should be added. The mode switch delay can be determined similarly, by observing the time for the system to "settle out" after a change from one mode of operation to another.

The heating coil, cooling coil, mixing box damper, temperature, flow, and enthalpy thresholds, and the maximum number of mode switches per hour are best determined by analysis of particular rules that are causing false alarms or are not reporting actual faults when the recommended parameter values are used. Although it is possible to apply a standard uncertainty, better results are obtained from trial and error. Trendlogs of the data relevant to the rule combined with a spreadsheet analysis of the rule can be very helpful for understanding why a particular rule is or is not reporting a fault, and then to help select better parameter values.

A detailed analysis of a particular rule will also reveal incorrect results that are due to poor values of the rule delay or the smoothing constant. If the rule delay is too short, transient conditions that are not true faults will cause false alarms, while a rule delay that is too long will cause real faults to be missed. If the smoothing constant is too great, noisy data or transient conditions that are not true faults will cause false alarms, while a smoothing constant that is too small will not allow real faults to be reported. A smoothing constant that is too small can also cause false alarms if the smoothed data still reflect the transient conditions from the most recent mode switch.

3.3.2.7 Tuning VPACC Parameters

Ideally, initial guesses for the expected value and standard deviation of the zone temperature, airflow, and discharge temperature errors should be calculated from data collected from the VAV boxes at the site. Data from unoccupied periods and from the first two hours of occupied periods should be removed from the set before computing the statistics. It is important to use data that is equally representative of heating and cooling conditions. If data are not available, the initial guesses for the expected zone temperature or airflow errors should both be set equal to zero. The initial guess for the expected discharge temperature should be set equal to the duct heat gain, which can be determined from the design documents or from measurements from a few typical VAV boxes. Sensor accuracies or typically observed variations can be used as initial guesses for the standard deviations. The recommended values from

Table 3 can serve as initial guesses for the remaining parameters.

Once initial guesses have been determined, the parameters can be tuned by observing the faults reported by VPACC compared to the actual performance of the system. If there are false alarms or missed faults from two or more of the errors, the alarm limit should be increased or decreased, respectively. If the missed faults or false alarms are from one error only, the standard deviation of that error should be adjusted instead. To eliminate false alarms early in the occupied period of the day, the occupancy delay should be increased. If false alarms occur late in the day, the CUSUM reset interval should be decreased.

The following example demonstrates the relationships between the parameters. In this example, the recommended values from

Table 3: VPACC Alarm Diagnoses are used. Consider a VAV box with a maximum airflow rate of 0.472 m^3/s (1000 cfm) and a constant airflow rate error of 0.07 m^3/s (150 cfm). The expected airflow rate error is zero and the airflow rate error standard deviation is equal to 0.02 multiplied by the maximum airflow rate, or 0.009 m^3/s (20 cfm). The normalized error will be constant:

$$z_i = (x_i - x_{exp}) / \sigma_{exp} = (0.07\ m^3/s - 0\ m^3/s) / 0.009\ m^3/s = (150\ cfm - 0\ cfm) / 20\ cfm$$

$z_i = 7.5$

Since the error is positive, only the positive (S) sum is accumulated. S is defined as:

$$S_i = max[0, z_i - k + S_{i-1}]$$

The expression is evaluated once per minute beginning 90 min (the occupancy delay) after the beginning of occupancy. Since all the terms are constant, S increases by

$$z - k = 7.5 - 3 = 4.5$$

each minute. After 223 minutes, S reaches a value of 1003.5, which is greater than the alarm limit of 1000. The CUSUM reset interval is 360 min, which is greater than the time to reach the alarm limit, so the alarm will be reported before S is reset to zero.

3.3.3 Test Sites

Previous research has established the performance of APAR and VPACC [1, 2, 3, 4, 5]. However, the primary goal of the field test was to evaluate the practicality and usability of embedding these FDD algorithms in commercial AHU and VAV box controllers. By involving controls manufacturers and dealers as well as building engineers in the study, the tools were evaluated under conditions as close as possible to those in which they will be used commercially. This approach was selected to ensure that any obstacles to commercialization would be revealed during the course of the test. Another goal was to evaluate modifications to APAR and VPACC for different system types. The field sites are described below.

SITE-1

SITE-1 was a private office building. APAR was embedded in the controllers of two VAV rooftop AHUs with hydronic heating coils and staged direct-expansion (DX) cooling coils. VPACC was embedded in 53 VAV box controllers, including 20 pressure independent, single-duct, parallel fan powered VAV boxes with hydronic reheat and 33 pressure independent, single-duct, throttling (no fan), cooling-only VAV boxes. Trendlogs of selected raw data, APAR rule violations, and VPACC alarms were configured. The trendlogs were archived and reviewed monthly. Personnel at the site responded to investigate and verify any reported faults.

SITE-2

SITE-2 was a large federal government office building in California. APAR was embedded in the controllers of two constant-volume AHUs with hydronic heating and cooling coils. VPACC was embedded in 1000 pressure independent, dual-duct VAV box controllers. Rather than configuring trendlogs, a computerized maintenance management system (CMMS) was configured to automatically generate a work order whenever a fault was detected. The building engineers responded to investigate, verify, and repair any faults reported through the CMMS.

SITE-3

SITE-3 was a private office building with some light industrial spaces. APAR was embedded in one VAV AHU with staged (combustion) heating and DX cooling coils. VPACC was embedded in the controllers of 46 pressure independent, single-duct, throttling (no fan), cooling-only VAV boxes. Trendlogs of selected raw data, APAR rule violations, and VPACC alarms were configured. The trendlogs were archived and reviewed periodically. Also, the building automation system's alarm/event handling function was configured to alert the operator whenever an APAR rule violations or VPACC alarm occurred. Each FDD event was also recorded in an alarm history database. Personnel at the site responded to investigate and verify any reported faults.

SITE-4

SITE-4 was a federal government building with a combination of office and laboratory spaces. APAR was embedded in the controller of one constant-volume AHUs with hydronic heating and cooling coils. Since the AHU controller operated in stand-alone mode (not connected to a network), selected raw data and APAR rule violations were logged by a stand-alone datalogging software tool running on a computer physically connected to the AHU controller. The trendlogs were archived and reviewed weekly. Personnel at the site responded to investigate and verify any faults that were detected.

SITE-5

SITE-5 was a large federal government office building. APAR was embedded in the controllers of two VAV AHUs with hydronic heating and cooling coils. VPACC was embedded in two pressure independent, single-duct, throttling (no fan) VAV boxes with hydronic reheat and two pressure independent, single-duct, throttling (no fan), cooling-only VAV boxes. Trendlogs of selected raw data, APAR rule violations, and VPACC alarms were configured. The trendlogs were archived and reviewed periodically. Also, the building automation system's alarm/event handling function was configured to record each FDD event in an alarm history database. Personnel at the site responded to investigate and verify any reported faults.

SITE-6

SITE-6 was a classroom building on a community college campus. APAR was embedded in the controllers of two VAV AHUs with hydronic heating and cooling coils. VPACC was embedded in 101 pressure independent, single-duct, series fan-powered VAV boxes with hydronic reheat.

Trendlogs of selected raw data, APAR rule violations, and VPACC alarms were configured. The trendlogs were archived and reviewed periodically. Personnel at the site responded to investigate and verify any reported faults.

SITE-7

SITE-7 was a museum building on a university campus. A specialized HVAC system maintains precise temperature and humidity conditions for the museum's artifacts; however, there is also a general purpose HVAC system for office and visitor spaces. APAR was embedded in the controllers of two VAV rooftop AHUs with hydronic heating coils and DX cooling coils. VPACC was embedded in nine pressure independent, single-duct, throttling (no fan) VAV boxes with hydronic reheat. Trendlogs of selected raw data, APAR rule violations, and VPACC alarms were configured. The trendlogs were archived and reviewed weekly. Personnel at the site responded to investigate and verify any reported faults.

SITE-8

SITE-8 was a classroom and office building on a community college campus. APAR was embedded in the controllers of one VAV AHU with hydronic heating and cooling coils. VPACC was embedded in 11 VAV box controllers, including 10 pressure independent, single-duct, parallel fan powered VAV boxes with electric reheat and one pressure independent, single-duct, throttling (no fan), cooling-only VAV box. The building automation system's alarm/event handling function was configured to alert the operator whenever an APAR rule violations or VPACC alarm occurred. Each FDD event was also recorded in an alarm history database. Personnel at the site responded to investigate and verify any reported faults.

3.4 Project Outcomes

A robust FDD application was developed using the APAR and VPACC rule sets

FDD code was developed using several manufacturers' application programming languages. Robust sets of parameters for APAR and VPACC were tabulated to enable the commercial use of these FDD tools without the collection and analysis of trend data from each potential installation. Recommended values for the parameters were determined through trial and error at multiple field test sites and the resulting values were compiled and tabulated. For users who need or prefer to determine site-specific parameters, procedures to do so were developed and documented.

The application was adapted to 8 sites. The data was trended and, where applicable, the data was accessed weekly through the internet, otherwise it was downloaded on site.

The first step was to gather specifications from the existing site and adapt the application to work with the existing structure. Then the control application was modified to incorporate the FDD algorithms and the data was trended along with the results from the FDD algorithm.

The FDD tools in the field performed as hoped and identified faults at every site. Multiple field sites were established to test APAR and VPACC embedded in commercial HVAC equipment controllers. The test was quite successful: a variety of mechanical and control faults have been detected, diagnosed, and in many cases, repaired. A representative subset of faults that were detected during the study is presented in the following pages. Table 4 summarizes the faults and their impact on the facility.

Table 4: Fault Summary and Impact

		Fault Impact				
Site	**Fault Description**	Energy Consumption	Indoor Air Quality	Occupant Comfort	Equipment Life	Maintenance Staff Productivity
SITE-1	Mixed Air Temperature Sensor Error	X				
SITE-1	Leaking Heating Coil Valve	X				
SITE-1	Outdoor Air Temperature Sensor Error	X				
SITE-1	Mechanical Cooling Fault			X		
SITE-1	Stuck VAV Box Damper Actuator	X				
SITE-1	VAV Box Maximum Airflow Setpoint Too High					X
SITE-1	Slipping Supply Fan Drive Belt				X	
SITE-1	Communication Failure	X				X
SITE-1	Undersized Supply Duct			X		
SITE-1	Disconnected Zone Temperature Sensor	X		X		X
SITE-2	Outdoor Air Temperature Sensor Error	X				
SITE-2	Chilled Water Not Available			X		
SITE-2	Airflow (DP) Sensor Drift	X	X	X		
SITE-2	Zone Temperature Sensor Failure	X		X		
SITE-2	Damper Actuator Failure	X		X		
SITE-2	Zone Temperature PID Loop Tuning Error				X	
SITE-3	Supply Air Temperature Error			X		
SITE-4	Hot Water Converter Offline			X		
SITE-4	Manual Override of Outdoor Air Damper	X				
SITE-4	Steam Outage			X		
SITE-4	Incorrect Cooling Coil Valve Actuator Configuration			X		
SITE-5	Simultaneous Mechanical Cooling and Economizing	X				
SITE-6	Simultaneous Mechanical Cooling and Economizing	X				
SITE-6	Outdoor Air Temperature Sensor Error	X				
SITE-6	VAV Box Controller Hardware Failure			X		X
SITE-6	Disconnected VAV Box Supply Air Duct			X		X
SITE-6	VAV Box Damper Actuator Failure	X				
SITE-6	Disconnected VAV Box Flow Sensor Tubing	X	X	X		
SITE-6	Zone Temperature Sensor Error	X		X		
SITE-6	Undersized VAV Box			X		
SITE-6	Undersized Supply Fan			X		
SITE-7	AHU PID Loop Tuning Error				X	
SITE-8	Zone Temperature Setpoint Too High	X		X		

3.4.1 Mixed Air Temperature Sensor Error

Figure 13: Mixed Air Temperature Sensor Error

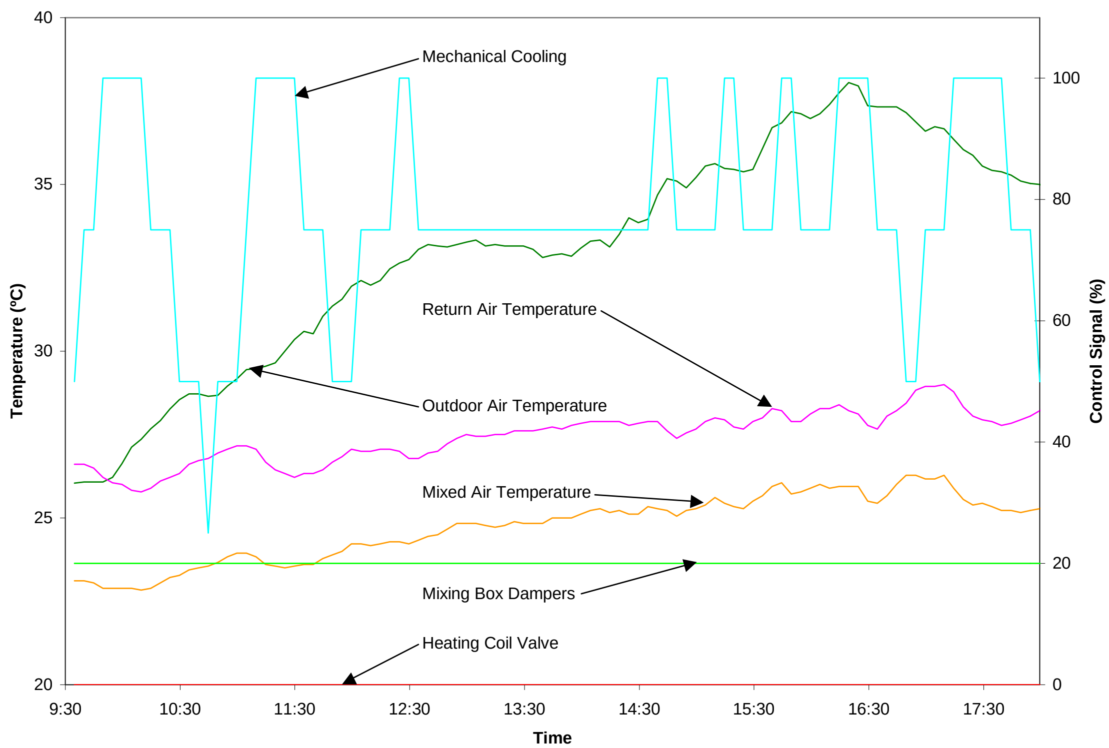


Figure 13 shows a plot of temperature and control signal data vs. time of day from one of the rooftop AHUs at SITE-1. The heating coil valve is fully closed and the mixing box dampers are positioned for the minimum outdoor air fraction needed to meet ventilation requirements (20 %). Stages of mechanical cooling are energized based on cooling requests from the terminal units served by the AHU. This combination of control signals corresponds to Mode 4: mechanical cooling with minimum outdoor air. In addition to the set of rules specific to Mode 4, there is a set of rules that applies to all occupied modes of operation (Table 1). One rule which applies to all occupied modes is Rule 26, which states that the mixed air temperature should be greater than the minimum of the return and outdoor air temperatures. For nearly the entire time period shown in Figure 3.1, the return air temperature is less than the outdoor air temperature, so according to Rule 26, the mixed air temperature should be greater than the return air temperature. However, Figure 13 shows that the mixed air temperature is less than the return air temperature by approximately 3 ºC. A trendlog showed that the APAR algorithm embedded in the AHU controller had generated a fault report due to Rule 26. As shown in Table 2: VPACC Diagnoses, the possible causes of this fault are a return, mixed, or outdoor air temperature sensor error. Onsite personnel investigated, determined that the mixed air temperature sensor had drifted out of calibration, and recalibrated it.

3.4.2 Leaking Heating Coil Valve

Figure 14: Leaking Heating Coil Valve.

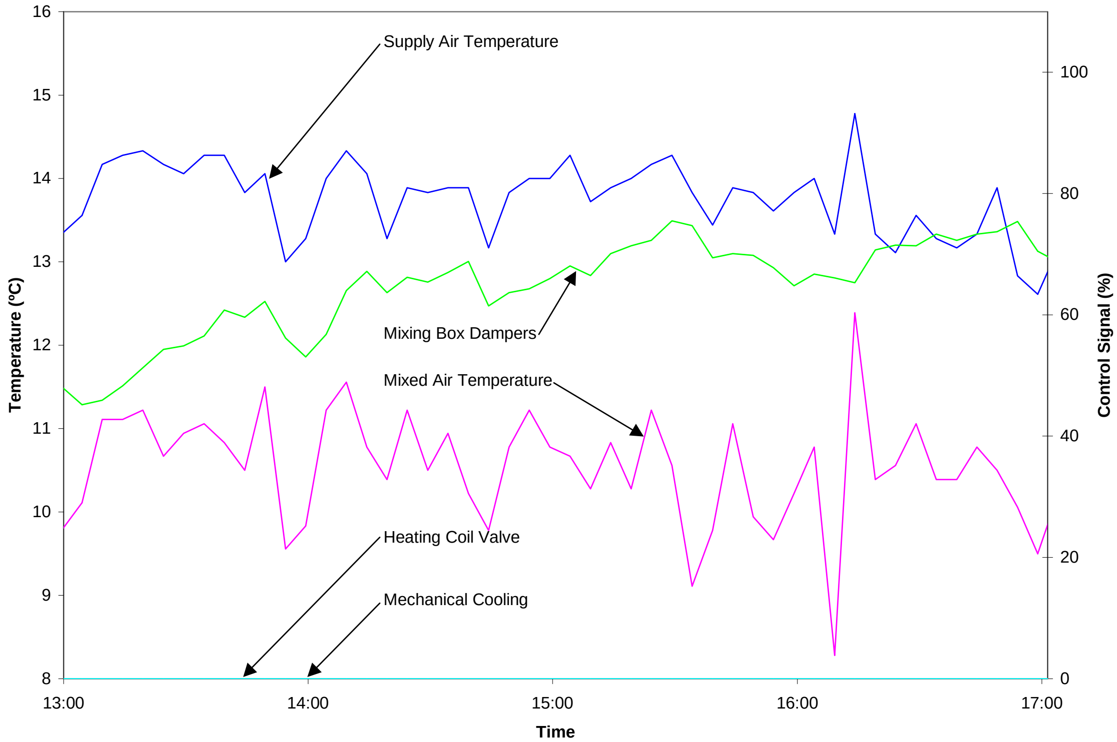


Figure 14 shows a plot of temperature and control signal data vs. time of day from one of the rooftop AHUs at SITE-1. The heating coil valve is fully closed and all stages of mechanical cooling are de-energized. The mixing box dampers modulate to maintain the supply air temperature at its setpoint (not shown). This combination of control signals corresponds to Mode 2: cooling with outdoor air. One of the rules for Mode 2 is Rule 7, which states that the supply air and mixed air temperatures should be nearly the same. Figure 14 shows that the supply air temperature is greater than the mixed air temperature by approximately 3 ºC. A trendlog showed that the APAR algorithm embedded in the AHU controller had generated a fault report due to Rule 7. As shown in Figure 14, the possible causes of this fault are a supply or mixed air temperature sensor error, a problem with the mechanical cooling system (since chilled water is not used), or a stuck or leaking heating coil valve. Onsite personnel investigated and determined that there was a leak in the heating coil valve.

3.4.3 Damper Actuator Failure

Figure 15: Damper Actuator Failure

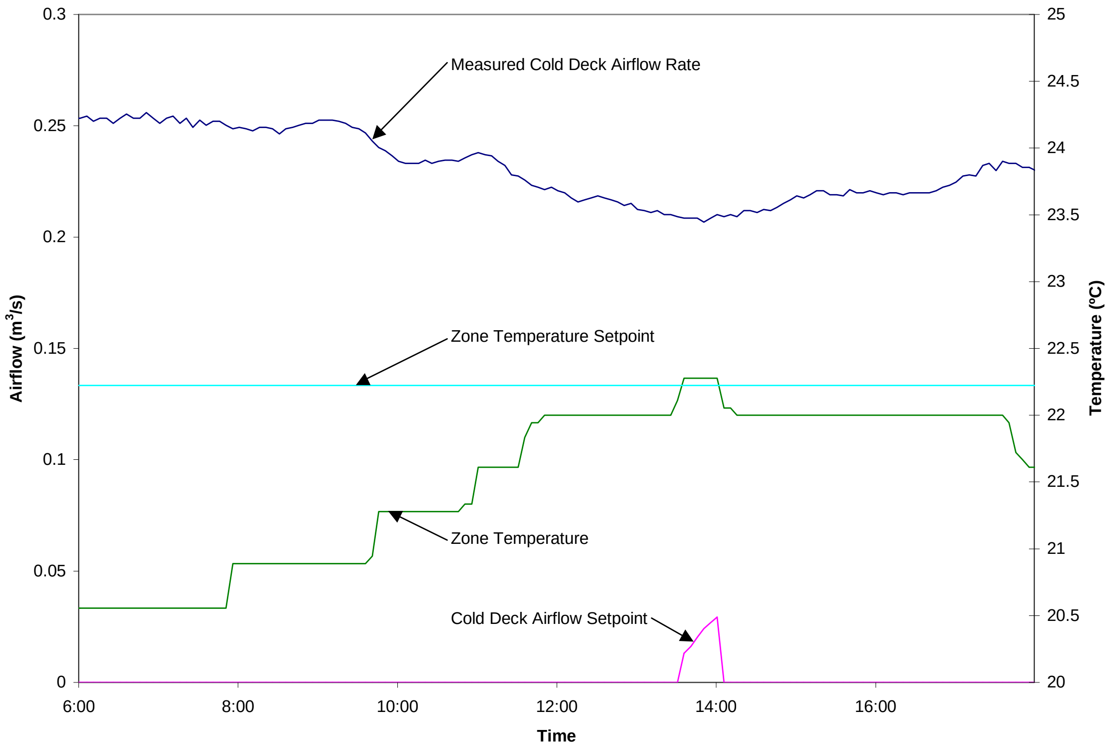
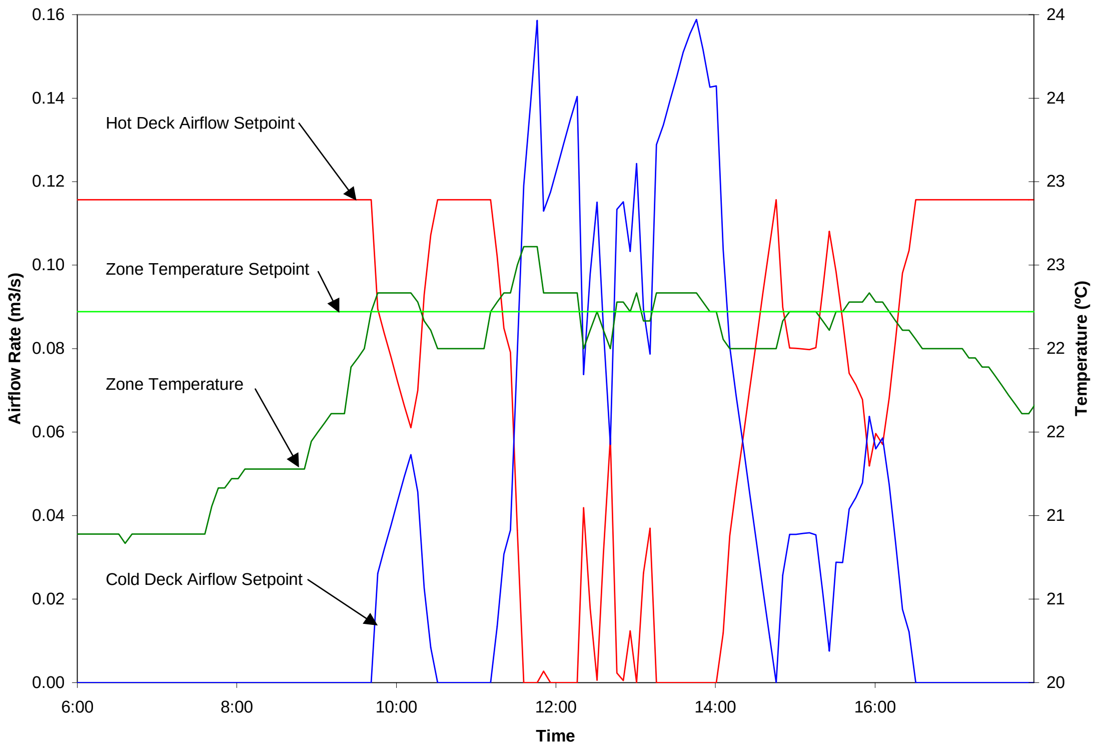


Figure 15 lists the possible causes of these faults, including a zone temperature sensor error, airflow (DP) sensor drift or failure, cold deck damper or actuator stuck or failed, supply air too cool, a scheduling conflict with the AHU, an undersized VAV box, a tuning problem with the airflow control or zone temperature control PID loop, an inappropriate zone temperature setpoint, a minimum airflow setpoint that is too high, and a sequencing logic error. This VAV box does not have a reheat coil, so the possible causes of reheat coil valve or actuator stuck or failed shown in Table 1 do not apply. Onsite personnel investigated and determined that the fault was due to a failed cold deck damper actuator. The damper failure allowed uncontrolled cold deck airflow to the zone, causing the zone temperature to fall well below the setpoint. The fault was repaired by replacing the broken actuator.

Figure 16: Zone Temperature Control Loop Tuning Problem



3.4.4 Zone Temperature PID Loop Tuning Error

Figure 16 shows a plot of airflow and temperature data vs. time of day from one of the dual-duct VAV boxes at SITE-2. It shows a negative zone temperature error, since the zone temperature is less than the zone temperature setpoint. A trendlog showed that the VPACC algorithm embedded in the VAV box controller reported a low zone temperature alarm. Table 3.3 lists the possible causes of this faults, including a zone temperature sensor error, airflow (DP) sensor drift or failure, supply air too cool, a scheduling conflict with the AHU, an undersized VAV box, a tuning problem with the airflow control or zone temperature control PID loop, an inappropriate zone temperature setpoint, a minimum airflow setpoint that is too high, and a sequencing logic error. This VAV box does not have a reheat coil, so the possible causes of reheat coil valve or actuator stuck or failed shown in Figure 16 do not apply. Onsite personnel investigated and determined that the fault was due to an under damped temperature control PID loop. The outputs of the zone temperature control loop are the hot and cold deck airflow setpoints. The hot and cold deck airflow control loops successfully maintained the hot and cold airflow rates (not shown) at their respective setpoints. Figure 16: Zone Temperature Control Loop Tuning Problem shows that as the zone temperature approached the setpoint, the temperature control loop oscillated, as seen in the varying hot and cold deck airflow setpoints.

3.5 Conclusions and Recommendations

The viability of deploying FDD as an integral component of the HVAC control system has been demonstrated. Based on feedback from users at the field sites, modifications have been made to enhance the usability and robustness of the FDD tools. In some cases, the local representative of the manufacturer of the control system was involved in the setup and operation of the test site. Feedback from these manufacturers' representatives, who will ultimately be responsible for installing FDD in their customers' buildings, was used to make the installation procedure more time- and resource-efficient and minimize the amount of site-specific configuration required.

CHAPTER 4:
Project 4: Advanced Package Rooftop Unit

4.1 Introduction

Research conducted under NBI PIER Element 4, Integrated Design of Small Commercial HVAC Systems (Commission Contract 400-99-012), produced performance guidance for designers and operators on ways to improve the efficiency and operations of small package HVAC units. Many of these improvements could be integrated into a new "advanced" rooftop unit (ARTU) that would directly address performance and market impact objectives.

This project's goals were to develop, test, and demonstrate an ARTU prototype of 5-ton cooling capacity that addresses many of the energy and ventilation problems found in commercial building mechanical systems. Features of the ARTU will include improved outdoor air control, improved economizer reliability, diagnostics and troubleshooting capability, and fault-tolerant design. The end result will be a unit that operates according to prevailing ventilation standards, reduces energy use and requires less maintenance.

4.2 Project Objectives

The objective of this task is to identify individuals with specialized technical expertise in the areas of packaged rooftop unit design, diagnostic systems for small packaged rooftop units, unit testing. These individuals will be recruited to serve on the TAG. TAG members will act as project advisors and review initial findings and suggest specific research refinements.

4.2.1 Identify Product Features

The objective of this task is to identify the product features to be implemented in the advanced packaged rooftop unit. The contractor shall compile all relevant background research material prior to developing the design specification for the ARTU. Energy savings estimates from the NBI PIER Element 4, *Integrated Design of Small Commercial HVAC Systems*, (Commission Contract 400-99-012) will be combined with incremental cost estimates to examine the cost effectiveness and marketability of the proposed design.

This project will develop and test an Advanced RTU prototype with a 5 ton cooling capacity that addresses the reliability of small commercial building mechanical systems, and the resulting energy impacts and ventilation problems (IEQ) found in these systems that result from unreliable, poorly controlled or out–of–tolerance systems.

Features of the ARTU will demonstrate the four main goals of the project:

1. Improved outdoor air control,
2. Improved economizer reliability,
3. On-board self-diagnostics and troubleshooting capability, and
4. Fault-tolerant design.

Features will be described that address:

- Economizer Improvements
- Fan Improvements
- Unit Efficiency
- Refrigeration Cycle Improvements
- Fan Controls
- Refrigerant Control
- Thermostat Capability
- Sensors
- Installation & Check-out Capability
- Advanced Monitoring
- Advanced Diagnostics

4.2.2 Develop Prototype ARTU

The objective of this task is to develop, in cooperation with Carrier, an ARTU that incorporates design features identified in the product definition task, Task 4.3. A preliminary set of specifications based on the NBI PIER Element 4, *Integrated Design of Small Commercial HVAC Systems*, (Commission Contract 400-99-012) was developed to guide the development of the ARTU. Issues addressed in the specification will be identified, and the detailed cost-benefit analysis will be undertaken to guide development of the specification. A first generation prototype ARTU will be developed in accordance with the specification.

4.2.3 Develop Test Plans

The objective of this task is to develop test plans for the economizer reliability, unit performance, and field test activities.

4.2.4 Test Prototype Unit in the Laboratory

The objective of this task is to test the unit in the laboratory to insure that the design meets the specifications. The first generation prototype will be taken to the SCE RTTF for detailed testing and analysis. A revised specification will be developed based on the results of the lab testing. Design modifications to the first generation prototype unit that comply with the revised specification will be completed.

4.2.5 Demonstrate Field Performance of Prototype

The objective of this task is to install the unit in a building to demonstrate the IEQ improvements and energy savings. Once the unit has been tested and certified to meet the specifications, a field demonstration of the unit performance will be conducted. IEQ improvements and energy savings will be documented during the field test.

4.2.6 Develop Tools to Reduce Market Barriers

The objective of this task is to develop tools that industry can use to develop, test, and rate the performance of advanced packaged units. To facilitate the adoption of the features of the ARTU by industry, a series of tools will be developed. A final specification for an ARTU will be prepared based on the results of the laboratory and field testing. Experience gained in the laboratory test will be used to develop a testing protocol that can be used by industry to test and validate the performance of ARTU features. A performance rating methodology that is responsive to the features covered in the ARTU specification will be developed to encourage the adoption of these features by industry. These testing and rating protocols will be presented to ASHRAE and ARI for consideration on a national level.

4.2.7 Market Connection Support

The goal of this task is to coordinate with the broader market connection tasks under Project 7, Market Connection.

4.3 Project Approach

4.3.1 Technical Advisory Group

Ten individuals were identified who consented to serve on the ARTU TAG. They were:

Name	**Affiliation**
Reid Hart	Portland Energy Conservation, Inc.
Jim Hussey	Marina Mechanical
David Jacot	Southern California Edison - Savings By Design
Afroz Khan	Consortium for Energy Efficiency (CEE)
Richard Lord	Carrier Corporation
Jim Mullen	Lennox Industries, Inc.
Todd Rossi	Field Diagnostic Services, Inc. (FDSI)
Harvey Sachs	American Council for an Energy Efficient Economy (ACEEE)
Ryan Stroupe	Pacific Gas & Electric Company

Note: Some of the above individuals are no longer affiliated with their original organizations.

4.3.2 Identify Product Features

The approach for this task involved the following steps.

Coordinate with other diagnostic research efforts (i.e. Purdue Univ., NIST, PNNL)

Coordinate with CEE advanced rooftop unit project

Compile all relevant background research material prior to developing the design specification for the ARTU.

Identify candidate RTU features to be implemented in the advanced packaged rooftop unit

Identify most useful diagnostic tests (systems monitored, data requirements, and analysis methods)

Identify context for diagnostic features (who is notified and how)

Prepare draft product definition summary report.

Combine energy savings estimates from the NBI PIER Element 4, Integrated Design of Small Commercial HVAC Systems, with incremental cost estimates for commercial units incorporating these new features, and examine the cost effectiveness and marketability of the proposed design.

Prepare draft report on cost/benefit assessment of the ARTU.

Finalize the product definition summary report in accordance with comments received during the Critical Project Review and with other information developed during the course of the project.

Finalize the cost/benefit assessment of the ARTU.

4.3.3 Develop Prototype ARTU

The approach for this task included the following:

Develop a preliminary set of specifications.

Specify unit control logic

- Specify diagnostic system sensor requirements and logic
- Specify thermostat and diagnostic system user interface requirements
- Specify efficiency targets
- Specify thermostat logic

Develop, in cooperation with Carrier, a first generation prototype ARTU that incorporates design features identified in the product definition task, Task 4.3.

Develop prototype controller/diagnostic hardware

Develop prototype controller/diagnostic firmware

Build the prototype controller

Assemble test unit

Prepare ARTU Product Design Specification

Mr. Dick Lord of the Carrier Corporation donated a stock five-ton 48PG “Centurion” rooftop unit for our baseline advanced RTU. The PG unit uses R-410a refrigerant and the SEER-14+ rating slightly exceeds the Energy Star minimum of SEER-13.

Mr. Todd Rossi and the staff of Field Diagnostic Services, Inc. (FDSI) developed the prototype controller/diagnostic system, and worked directly with Carrier to integrate ARTU control and FDD features with the Carrier monitoring software.

4.3.4 Develop Test Plans

The approach for this task originally included the following:

Review existing test standards for RTUs, dampers, and controls

Develop draft economizer reliability test plan

Develop draft ARTU performance test plan

Develop draft field test plan

4.3.5 Test Prototype Unit in the Laboratory

The approach for this task originally involved the following steps.

Design and construct economizer reliability test hardware

Conduct reliability tests at Southern California Edison's Refrigeration & Thermal Testing Center (RTTC) in Irwindale, CA (SCE's RTTF).

Prepare reliability test report

Set up unit for performance testing in SCE RTTF test chamber

Conduct performance tests - control function

Conduct performance tests - diagnostic system function

Conduct performance tests - unit efficiency under fault conditions (fault tolerance)

Prepare unit performance test report

Modify unit and/or controller based on test results

Revise the product specification based on the results of the laboratory tests

4.3.6 Demonstrate Field Performance of Prototype

The approach for this task originally involved the following steps.

Identify a developer willing to have the unit installed on a building

Acquire instrumentation

Install instrumentation on existing unit on building

Perform "pre" demonstration data collection/analysis of existing unit

Remove existing unit and install new ARTU

Commission new ARTU

Reinstall instrumentation on ARTU

Perform data collection/analysis of ARTU

Remove ARTU at conclusion of test, return site to original condition

Prepare field test report

The Field Performance task was cancelled. A consensus was reached during the early phases of research that field testing for a six-month duration, as originally proposed, would not likely reveal information that cannot be discovered during the laboratory testing task.

4.3.7 Develop Tools to Reduce Market Barriers

The approach for this task originally included the following:

- Prepare an economizer reliability test protocol.
- Prepare a final specification for an ARTU based on the results of the laboratory testing.
- Use experience gained in the laboratory test to develop a unit performance testing protocol that can be used by industry to test and validate the performance of ARTU features.
- Develop a unit performance rating methodology that is responsive to the features covered in the ARTU specification to encourage the adoption of these features by industry.

The economizer reliability test was cancelled. Most of the identified features were incorporated in a prototype ARTU, which was then subjected to laboratory testing. The original scope of work for the ARTU project included an economizer reliability test and subsequent report. However, manufacturers are already developing improved economizer hardware and trending away from problematic linkages. It became unclear what would be gained by testing one more economizer. For this reason as well as schedule and budget constraints, the Project team and the Commission Manager for the FDD Program determined that such a test and report would not be necessary.

4.3.8 Market Connection Support

The approach for this task involved coordinating with the New Buildings Institute under Project 7, Market Connection. Also included was the development of a Technology Transfer Plan.

The approach was amended to include coordinating with the Consortium for Energy Efficiency (CEE) and CEE members to help update CEE's specifications for tiered performance levels for rooftop air conditioning units. This would include a specification for an ARTU, which CEE may adopt as its own specification. Working with CEE was considered an expedient way to encourage and demonstrate how manufacturers can integrate advanced features into their standard product lines, and to encourage utilities to reference the ARTU specification as part of their market transformation rebate and design support programs.

4.4 Project Outcomes

4.4.1 Identify Product Features

This task developed a list of product features that define an Advanced Packaged Rooftop Unit (ARTU)". Existing rooftop units have documented problems, and by combining the expertise of the members of the project's Technical Advisory Group (TAG) and the research team, and with the funding provided by the California Energy Commission, we can help solve many of these problems. We further believe that we can identify particular "features" that an ARTU should have, and that incorporating these features in a demonstration rooftop unit would provide value to the manufacturing, contracting, utility and energy communities.

As part of this project, a number of features were identified that, if incorporated in manufactured units, could define an "advanced" RTU. Features are classified into eleven "categories," including economizer improvements, fan improvements, unit efficiency, refrigeration cycle improvements, fan controls, refrigerant control, thermostat capability, sensors, installation & check-out capability, advanced monitoring, and advanced diagnostics.

It is hoped that by incorporating these features in their rooftop unit product lines, manufacturers can increase the reliability and in-field performance of rooftop units, thereby reducing the amount of degradation over time that has been observed in the past. Avoiding such degradation will raise the long-term energy performance of HVAC equipment.

The main features of the ARTU were selected by the Technical Advisory Committee. The Product Definition document then guided the assembly of a prototype ARTU. The unit was then tested to demonstrate the feasibility and effectiveness of the incorporated features.

The starting point for these definitions was the draft "Preliminary Specification for an Advanced Packaged Rooftop Unit (ARTU)," originally dated July 17, 2003, developed by the Consortium for Energy Efficiency (CEE). This document was chosen because a number of parties in the research community are familiar with it and are anxious to see the work continued. Successful implementation of the various features in an ARTU would have significant impact on the reliability, operating and maintenance costs, and energy usage for air-conditioning equipment in the State of California and, eventually, nationwide.

The CEE "specification" was more a proposed list of provisions or "features" for an advanced rooftop unit than a traditional (i.e., Construction Specification Institute (CSI) format) specification for air handling units. CEE divided their features into three "Tiers," but this ARTU project, the features were sorted into three "Levels" since the "Tier" terminology conflicts with other meanings in the industry. The term "Level" has the following definitions:

LEVEL 1 is a set of <u>features that are all currently available</u> on the market, can be requested today, and are fundamental to improving field efficiency and performance. Although some of these features are not routinely purchased with basic systems today, features in this level are intended as the foundation requirements of an advanced roof top unit.

LEVEL 2 incorporates the features in Level 1, plus <u>additional design features</u> that create a new Advanced Rooftop Unit (ARTU) that can deliver greater field efficiency and performance. <u>These features may not be readily available on the market, but some are a part of a development and testing project</u> underway through California Public Interest Energy Research and manufacturing partners.

LEVEL 3 is a set of proposed performance-based measurements for <u>future specification</u> development. In the course of exploring in-field performance problems affecting efficiency, CEE found that there was a lack of performance-based measures and test protocols to address these aspects of performance. As a result, CEE identified a number of measures that would be useful in developing a performance-based specification.

Level 1 features and many of the Level 2 features identified in this project are currently incorporated into "Tier 2" HVAC systems available from most manufacturers. In industry terminology, "Tier 1" equipment meets minimum efficiency and product specifications, and "Tier 2" is Energy Star compliant or equivalent. Industry's "Tier 3" equipment includes features justified by lowest life-cycle cost and highest annualized efficiency, which includes the balance of this project's Level 2 features. Level 3 features are not yet available in manufactured equipment and require further technological development.

The intent of this project is to demonstrate that incorporation of Level 1 and Level 2 features can increase the reliability of rooftop units, as well as raise the baseline energy performance for HVAC equipment beyond the current "Tier 1" and "Tier 2" efficiency benchmarks.

For complete discussion and further detail on the elected features, please see Project 4: Advanced Rooftop Unit Deliverable D4.3c – *Final ARTU Product Definition Report*, dated September 13, 2005. In that report, each feature is described and the reasoning behind its inclusion (or rejection) is presented. Level 1 and Level 2 features, taken together, constitute the "Product Definition" of an "advanced" unit in that such a unit incorporates features that are readily available today as well as new beneficial features that will be available "soon" or are presently in development. The end product will be a new rooftop unit incorporating a set of features that hopefully defines a new "standard" unit with better outside air control, economizer reliability, on-board diagnostics and fault-tolerance than existing units marketed today.

Additional features were conceived, but ultimately did not make the final list or ARTU requirements. Level 3 features are considered worth studying further, but may be too difficult to implement in the near term. Level 3 features are included in the ARTU Product Definition as targets for future development, since, while they would provide a benefit to the industry, they are considered to be beyond near-term availability. Manufacturers and control systems developers are asked to consider such features when they develop new products and capabilities. Level 3 features that this project has considered are listed after the Level 1 and Level 2 features group.

Features that have been discussed during this task, but that we ultimately decided not to incorporate, are listed after the ARTU Product Definition. These "rejected" features, although potentially beneficial in some way, may increase energy use, be unreliable or misleading to the building owner, or be too expensive to implement, etc. These additional features are not part of the present specification, but are listed in the ARTU Product Definition to provide an overview of additional items that were considered.

An abbreviated list of ARTU features is provided below.

4.4.2 ARTU Incorporated Features – Level 1 and Level 2

Level 1 features that are either available in the marketplace already, or are near-market ready, and are considered vital to improving field efficiency and performance. Again, these features are intended as the baseline requirements of an advanced roof top unit. Level 2 features that are suggested features that should be able to be implemented without too much difficulty.

4.4.2.1 Economizer

Factory installation

Direct drive/permanent lubrication

Differential dry-bulb or enthalpy control, or dewpoint control

DCV capability

Compressor lockout on low OAT

Economizer modulation on low OAT

Dead band @ 2degF or less

2- to 5-year factory warranty on economizer parts and labor

Low-leakage RA damper @ 2%

4.4.2.2 Fans/Fan Control

Power limitation per ASHRAE 90.1

Continuous SF operation during occupied hours

4.4.2.3 Unit Efficiency

Rated efficiency per CEE "Tier 2." (Supersedes Energy Star compliant)

4.4.2.4 Refrigeration

R410a

Improved-efficiency condenser fan motor (e.g., ECM or PSC)

TXV, EXV or similar adjustable device

4.4.2.5 Thermostats

Commercial grade

Dual setpoint, min. 5-degF deadband, continuous fan operation, time-of-day/weekend/holiday programming, temporary override

Integrated economizer capability

Occupancy sensor interface

4.4.2.6 Sensors

Accuracy requirements +/- 1degF

Solid-state electronic humidity elements

Connections designed to prevent misconnection

CO2 sensor supplied by control mfr

4.4.2.7 Installation and Check-out Capability

Refrigerant line labels if multiple circuits

Hi-Pressure liquid line port, low-Pressure suction port

Ports accessible w/o removing panels

Min-Outside Air adjustments accessible w/o removing panels

4.4.2.8 Advanced Monitoring

Permanent sensors, readings displayed at controller

Controller indicated enabled operating mode, including economizer

Ability to initiate tests of operating modes

4.4.2.9 Advanced Diagnostics

8-bit (min) digital resolution

Detect faulty sensors and send notification signals

Detect faulty economizer and send notification

Detect and signal evaporator air temperature difference out of range

Detect and signal refrigerant charge out of range

Other faults

4.4.3 Level 3 - Features Considered for Future Development

The following tables show Level 3 features that should be considered in the future development of an Advanced Rooftop Unit. These included:

Economizer test standard-industry wide support needed

Turning vanes for horizontal-discharge units

Multi- or variable-speed SF interlocked with compressor and OA damper

Intelligent night flush mode

Improve installation and O&M literature (especially economizer, DCV and CO2 setup, sensor calibration)

Ability to override sensors

Interface with central control system or device

Data collection and storage

4.4.4 Additional Features Considered but Not Incorporated

Some additional features were considered for use in an Advanced Rooftop Unit, but were not incorporates into this preliminary specification. The following tables note the features that were considered, as well as the rationale for not incorporating them into the specification.

A number of features that were examined by the TAG were ultimately rejected for incorporation for a variety of reasons from a cost, benefit or potential complexity. Background discussion for each decision to not incorporate a given feature is provided in the *Final ARTU Product Definition Report:*

- Relief dampers in lieu of powered exhaust
- VS exhaust / return fan proportional to OA damper
- Relief air directed to condenser coil in cooling season
- MTBF of 15 years for economizers and sensors
- Further limitation on SF power per CFM
- Premium efficiency supply fan motor
- Direct drive SF motor
- Toothed belt drive and automatic tensioning
- Cabinet leakage not to exceed 2%
- High-efficiency evaporator
- High-efficiency condenser
- Liquid-to-suction HX
- Refrigerant receiver
- Specified minimal loss of efficiency on wide range of charge variation
- Independent H/C/Fan programming
- Manual UN-occupied mode at thermostat
- Read-out of OA percentage

4.4.5 Cost-Benefit Assessment

An important aspect of new or improved product is, of course, cost. It does no good to define requirements for product improvements if they are too costly to implement on a wide scale. Therefore, a cost-benefit analysis was developed for the ARTU, and the results of that analysis are presented in detail in a separate report. That document presents an analysis of the costs and benefits associated with the features related to an advanced rooftop unit (ARTU).

These 36 features identified in the "ARTU Product Definition Report" (AEC 2005) are divided into four groups for the cost assessment:

1. Operational Performance
2. Maintenance and Serviceability
3. Reliability and Robustness
4. Diagnostics and Monitoring

The costs and benefits assessed relate to a 5-ton electric cooling, gas heating rooftop unit, a common HVAC system found in small commercial installations.

For this analysis, a basic "off the shelf" rooftop unit, called the "baseline RTU", is compared with a rooftop unit that incorporates all of the ARTU features. The baseline RTU costs are based on the 5-ton Carrier 48HJ (a basic rooftop unit that has only a few ARTU features and that just meets ASHRAE 90.1-2004 energy efficiency requirements), and the ARTU costs are based on the 5-ton Carrier 48PG. The costs related to the advanced fault detection and diagnostics features not already included in the ARTU were obtained from other studies (Li-Braun 2007, AEC 2005).

The Carrier 48PG includes additional features not included in the ARTU list of features, so the 48PG cost may be higher than the cost of a basic rooftop unit with ARTU features added. These additional features include a slide out fan assembly for cleaning and motor change ease, a slide out condensate pan for cleaning, and access ports for condenser coil cleaning. Also, the Carrier 48HJ unit already includes a few ARTU features, e.g., 8-03 (sensors that are not polarity sensitive are used) and 9-04 (controls to adjust minimum outside air position are accessible with air plenum panels in place). For this analysis, a 10% deduct to the 48PG material cost is applied to account for features included in the unit that are beyond the list of ARTU features and a 10% deduct to the 48HJ material cost is applied to account for ARTU features already included in this unit. Note, however, that the labor to install a unit and the contractor overhead and profit values will not change despite the 10% reduction in material costs. Therefore, the overall reduction in *installed* costs has been estimated at approximately 9.2%. The feature-specific discussions in the following sections include details regarding the latter, where the Carrier 48HJ already includes ARTU features.

Installed cost estimates for the after-factory ARTU features related to advanced fault detection and diagnostics (FDD) range from $250-$600 (Li-Braun 2007) to $500 (AEC 2005, assuming four rooftop units per site). However, the Carrier 48PG unit already has approximately 70% of the recommended FDD features installed as part of the control package. Therefore, an additional $150 cost has been applied to account for the enhanced FDD features not already included in the Carrier 48PG unit.

Table 5: Cost Summary, Baseline/Final.

Unit	**Base Installed Cost**	**Final Installed Cost***
Baseline RTU (based on Carrier 48HJ)	$6,200	**$5,700**
ARTU (based on Carrier 48PG)	$10,500	**$9,800**
	Cost Differential	**$4,100**

* Baseline RTU includes 9.2% installed cost deduct to account for ARTU material features already included in Carrier 48HJ model. ARTU includes 9.2% installed cost deduct to account for Carrier 48PG material features beyond current list of ARTU features, as well as $150 for enhanced FDD features.

The installed costs shown in Table 5 include material, labor, installing contractor's overhead and profit, general contractor's mark-up, and a factor to adjust costs to California for a 5-ton electric cooling, gas heating rooftop unit with controls and an airside economizer section. Labor, overhead and profit, and local cost adjustment values were estimated based on an industry-standard cost estimating guide (RSMeans 2007). The Carrier 48PG costs also include the $150 material cost related to the enhanced FDD-related ARTU features not currently installed on the 48PG unit. As indicated in the table, the difference in installed cost between the baseline RTU and the ARTU is $4,100.

Costs at the detailed level of individual components and control programming are not readily available.

4.4.5.1 Benefits

Both energy and non-energy benefits are realized by adding the ARTU features to the baseline RTU. The energy-related benefits were estimated using the following methods:

- Modeling a simple retail building using eQUEST, a DOE-2 building energy use simulation. Simulations were performed for three locations in California with different climates (San Diego, Sacramento, and Palm Springs); the building in each city was sized to match the cooling capacity of the 5-ton baseline RTU. The energy use outputs for each city were then averaged. With the building characteristics fixed, the HVAC system was then changed to simulate the ARTU features and the simulations were rerun. The energy benefits for 14 of the 29 energy-related ARTU features were estimated through the use of these energy simulations.
- Incorporating energy use data from previous research related to small packaged RTUs (Jacobs 2003).

Some of the energy benefits relate to avoided energy cost. For example, the annual energy cost for operating a rooftop unit with an improper refrigerant charge is, on average, $12 more than the energy cost for a properly charged rooftop unit. This $12 is included in the energy-related benefits, since incorporating the ARTU feature related to self-monitoring refrigerant charge through advanced diagnostics (feature 11-05) would help to keep the unit operating at the proper charge.

The non-energy benefits of the ARTU features relate to annual saved service time. For example, the feature related to locating the refrigerant pressure ports outside the condenser fan plenum (feature 9-03) is estimated to save one hour ($90) of service time per year, since the condenser fan plenum will not have to be removed and replaced each time these refrigerant pressures are measured. The non-energy benefits of the ARTU features apply to those located in the Maintenance and Serviceability group.

Both energy and non-energy benefits are realized by adding ARTU features to the baseline RTU. The cumulative benefit for all of the ARTU features will be lower than the sum of the individual ARTU feature benefits due to the overlap between features. For example, the benefits related to features 1-01 (factory-installed economizer), 1-02 (direct drive modulating economizer actuator, gear driven economizer interconnections, and permanently lubricated bushings or bearings on economizer dampers), and 1-08 (economizer systems factory warranted for five years) include energy savings related to a fully functioning economizer. Summing these benefits would give exaggerated savings estimates.

The estimated annual energy and non-energy savings related to the cumulative ARTU features are summarized in the following table. These savings are averaged over a number of units, and would not necessarily apply to one individual unit. For example, the savings related to a fully functioning economizer (Reliability & Robustness sub-group) is based on research that found 63% of installed rooftop units operating with a failed economizer; this would not be the savings seen by any one particular unit, but would be a site average.

Table 6: Benefits Summary

Group or Sub-Group	**Number of ARTU Features**	**Annual Energy Benefit**	**Annual Non-Energy Benefit**
Physical Hardware			
Operational Performance	18	$240	
Maintenance and Serviceability	7		$200
Reliability and Robustness	8	$30 - $260	
Diagnostics and Monitoring	3	$30	$100
Subtotals		$300 - $530	$300
Total	36	$600 - $830	

The estimated total cost for incorporating the 36 ARTU features into a basic 5-ton rooftop unit is $4,100. The estimated annual combined energy and non-energy benefit related to the ARTU features is between $600 and $830. This gives an estimated simple payback time of between 4.9 and 6.9 years.

For a complete discussion of ARTU costs and benefits, plus details of the energy simulation model, please refer to Project 4: Advanced Rooftop Unit Deliverable D4.3e – *Final ARTU Cost-Benefit Analysis*, dated October, 2007.

4.4.6 Develop Prototype ARTU

During the prototype development phase of the ARTU project, a 5-ton Carrier rooftop unit, Carrier model 48PG ("Centurion" series), was modified to incorporate as many ARTU features as possible. The stock unit already includes many ARTU features, and is Carrier's premium rooftop unit. Features of this Carrier unit are compared to features of the baseline unit in Table 7.

Table 7: Carrier Rooftop Unit Comparison

Component	Carrier 48HJ ("Baseline RTU")	Carrier 48PG ("ARTU")
Cooling efficiency	SEER 13	SEER 14
Heating efficiency	81% steady-state thermal efficiency	81% steady-state thermal efficiency
Control	Electro-mechanical	Microprocessor-based
Economizer	• Field-installed • Non-integrated • Single point temperature-based control • One year standard warranty	• Factory-installed • Integrated • Differential enthalpy-based control • Five-year warranty
Thermostat	• Residential-style • Programmable	• Commercial-style • Programmable • With CO_2 sensor
Refrigerant	R-22	R-410A

4.4.7 Develop Test Plans

A detailed step-by-step test plan was developed to direct the activities of the laboratory tests. Please refer to Project 4: Advanced Rooftop Unit Deliverable D4.5d – *Final ARTU Performance Test Plan,* dated April 4, 2006, for further information.

Most of the identified ARTU features were incorporated in a prototype ARTU, which was then subjected to laboratory testing. The original scope of work for the ARTU project included an economizer reliability test and subsequent report. However, manufacturers are already developing improved economizer hardware and trending away from problematic linkages. It became unclear as to what would be gained by testing one more economizer. For this reason as well as schedule and budget constraints, the Project team and the Commission Manager for the FDD Program determined that such a test and report would not be necessary.

4.4.8 Test Prototype Unit in the Laboratory

In an attempt to provide demonstrated value to the manufacturing, contracting, utility and energy communities, many of the defined ARTU features were incorporated in a demonstration rooftop unit with a five ton cooling capacity. This prototype ARTU was subsequently tested at Southern California Edison's Refrigeration & Thermal Testing Center (RTTC) in Irwindale, CA by Ramin Faramarzi (Manager), Bruce Coburn, John Lutton and Scott Mitchell. The intent of the tests was to demonstrate that the features chosen for the ARTU are reasonable and achievable without undue effort, thereby easing their adoption by rooftop unit manufacturers.

Several features do not have test requirements. For example, one feature is to provide an extended warranty for economizers. In order to be able to offer such a warranty, manufacturers will need to be confident that their economizers are likely to remain functional and within reasonable calibration for the warranty period. Providing the warranty meets the intent of the feature, but there is no test involved.

Some of the features have multiple test points. For example, the ability of the controller to send a diagnostic alert upon detecting a fault is one feature, but there are ten faults for which it tests – failed compressor, failed fan motor, dirty filter, dirty coil, etc.

Product development and testing assistance were provided by Todd Rossi (President) and Changlin Sun of Field Diagnostic Services, Inc. (FDSI).

The ARTU deliverable 4.6d, *Unit Performance Test Report*, presents the results of the testing. Altogether, there are 30 feature points that were tested and 26 that were not. Of the 30 tested points, 26 "passed" their test, meaning that the feature was incorporated and was successfully demonstrated in the lab. A summary of the features and, if applicable, the lab test results are presented in Project 4: Advanced Rooftop Unit Deliverable D4.6b –*ARTU Performance Test Report*, dated December 15, 2007; they also appear in the Project 4: Advanced Rooftop Unit Deliverable D4.1d – *Final Report, Project 4: Advanced Rooftop Unit*.

4 4.9 Develop Tools to Reduce Market Barriers

4.4.9.1 ARTU Unit Performance Test Protocol

To show the near-term feasibility of incorporating ARTU features, and thus provide value to the manufacturing, contracting, utility and energy communities, a demonstration advanced rooftop unit was developed and run through a series of tests in a laboratory facility, Southern California Edison's Refrigeration and Thermal Test Center (RTTC). The results of those tests are found in another document[2]. The intent of this demonstration is to show that incorporating Level 1 and Level 2 features, some of which are only presently found in higher-end products now in the marketplace, are not that difficult to achieve and to encourage the migration of such features to lower-tier HVAC units. Since such units are quite commonly installed in commercial buildings, it is believed that the wide-spread adoption of ARTU features can increase the reliability and field performance of rooftop units, thereby reducing maintenance requirements, increasing the lifetime of these units and avoiding the long-term energy waste that result from undetected degraded operating conditions

[2] "*ARTU Performance Test Report,*" Advanced Automated HVAC Fault Detection and Diagnostics Commercialization Program, California Energy Commission Contract # 500-03-030, Project 4: Advanced Rooftop Unit Deliverable D4.6b, December 15, 2007.

Following the laboratory test phase, the results and lessons learned were used to develop several tools that industry can use to develop, test, and rate the performance of advanced packaged units. These tools are:

A final specification for an ARTU, based on the results of the laboratory testing.

A testing protocol that can be used by industry to test and validate the performance of rooftop units as related to ARTU features.

A performance rating methodology that is responsive to the features covered in the ARTU specification and the test protocol , for manufacturers to use as a checklist and score sheet to gauge the degree to which new units successfully attain ARTU "status".

The testing protocol can be used for any Advanced RTU prototype developed in response to this research to verify that improvements have been installed and perform as intended. It presents procedures and templates with which the results of testing of candidate ARTUs can be recorded in a consistent format. The protocol is based on test procedures developed by the RTTC.

The "ARTU Performance Test Protocol" provides a guideline with which manufacturers can evaluate their rooftop products against the ARTU definition.

There are 36 ARTU features defined in the Product Definition Final Report. Several features do not have test requirements. For example, one feature is to provide an extended warranty for economizers. In order to be able to offer such a warranty, manufacturers will need to be confident that their economizers are likely to remain functional and within reasonable calibration for the warranty period. Providing the warranty meets the intent of the feature, but there is no test involved.

Some of the features have multiple test points. For example, the ability of the controller to send a diagnostic alert upon detecting a fault is one feature, but there are ten faults for which it tests – failed compressor, failed fan motor, dirty filter, dirty coil, etc.

Altogether, as of this writing, there are 30 feature points that lend themselves to testing and 26 that do not. The RTTC tested these points in the prototype unit using the methodology presented below. Each test is designed to confirm first, that the ARTU is running properly, and second, to verify that the incorporated feature functions as intended.

For a detailed description of the ARTU features and the reasons why each was selected, please refer to the *ARTU Product Definition Final Report*.

4.4.9.2 ARTU Unit Performance Rating Methodology

The Rating Methodology can be used in conjunction with the ARTU Test Protocol to verify that improvements have been installed and perform as intended. It presents a scoring worksheet to evaluate the advanced features of candidate ARTUs. It is based on advanced features defined in the ARTU Product Definition report, previously issued.

To determine whether a packaged rooftop unit meets the qualifications for a CEE ARTU designation, if the RTU or its controls have the indicated feature, fill in "Yes" in the "Feature Provided?" column and fill in the number of available points in the "Earned Points" column.

Please refer to Project 4: Advanced Rooftop Unit Deliverable D4.8g –*Final ARTU Performance Rating Methodology,* dated October 2008, for the complete methodology details.

4.4.10 Market Connection Support

The Market Connection Support task focused mainly on the ARTU Technology Transfer Plan. This is one of a series of Technology Transfer Plans in the PIER Advanced Automated HVAC Fault Detection and Diagnostics Commercialization Program (FDD). In the FDD program, "technology transfer" is defined broadly to mean everything needed to move the product from its current developmental state to successful market introduction. Each of the FDD's technology transfer plans addresses one of the FDD's technology or protocol products, and provides an overview of the product's development status, markets, and a business case. Most importantly, it identifies specific actions recommended to encourage the product's production and successful market introduction in California.

Please refer to Project 4: Advanced Rooftop Unit Deliverable D4.9b –*Final ARTU Technology Transfer Plan,* dated December 2008, for the complete Plan.

4.5 Conclusions and Recommendation

4.5.1 Product Features

While considerable time and effort was expended to develop the ARTU features set, there may yet be room for improvement. In the coming months and years, features presently considered "advanced" may become commonplace or "standard," or features presently reserved for future development may become of more immediate interest to the HVAC community and consumers. Thus, the existing features set, as defined in this and other supporting documents, should not be considered locked in, but capable of evolving as priorities change and improvements in technology advance.

4.5.2 Develop Prototype ARTU

During the course of the ARTU project, in order to gauge how close the marketplace presently is to having "advanced" units available, features of several commercially available rooftop units were compared to the ARTU features set. Several of the major manufacturers already have some of the ARTU features available, but no manufacturer has all of the features. It is recommended that this tracking effort be continued as a way to follow the progress of the industry. No commercial unit may ever have all the ARTU features defined by this project, but that is to be expected as priorities shift. Furthermore, as new features not envisioned by this project are introduced, what constitutes an "advanced" unit is sure to evolve. By continuing to track rooftop unit developments, areas of special interest and needs for future research may be identified.

4.5.3 Cost-Benefit Assessment

The Cost-Benefit Assessment should continue to be refined.

Benefit estimates were made using information from previously published reports, energy modeling software, and service estimates. As indicated in the report, the estimated cost for incorporating the ARTU features in a basic 5-ton rooftop unit was determined to be $4,100. The annual combined energy and non-energy benefit related to the ARTU features is between $600 and $830. This gives a simple payback time of between 4.9 and 6.8 years. Continuing assessment would indicate how the payback and life-cycle benefits improve as ARTU features are more widely adopted.

Besides the actual cost of the ARTU features, production quantities could also be a factor in the cost difference. The number of "ARTUs" sold in the U.S. is currently only 5% of the number of basic rooftop units sold. This large production difference could also be influencing the cost difference between a RTU and an ARTU.

Commercially available rooftop units that include most of the ARTU features are popular in owner-occupied buildings. Many of the ARTU features relate to serviceability and reliability, not just base energy efficiency. The building owners appreciate the robustness of these units, and recognize the value of the additional diagnostics and ease of maintenance.

4.5.4 Remaining Steps to Market Readiness

Market Connections activities were to focus on working with CEE and its members to develop performance level specifications, including an ARTU specification, informed by the ARTU prototype developed and tested in this project, in order (1) to encourage and demonstrate how manufacturers can integrate advanced features into their standard product lines and (2) to encourage utilities to reference the ARTU specification as part of their market transformation rebate and design support programs. The second focus has become the primary focus given how reluctant the HVAC industry is to be 'pushed' too hard on making improvements across major product lines.

Architectural Energy Corporation staff and New Buildings Institute staff are working with CEE staff to establish a statement of work for CEE utilities to initially assess which features of the ARTU can be incentivized based on confidence in the energy or demand savings projections for the individual features. The utilities will make their own assessment of how to establish the energy benefits of ARTU features. That step leads to consideration of which measures either individually or in packages, might receive utility financial support. The next step is assessing the features that are less amenable to engineering calculations of savings, but are still considered very important to maintaining performance.

Following a comprehensive review and selection of the measures and/or packages of measures, development of educational materials and marketing approaches would begin. Utilities would then be positioned to make the recommendations for the ARTU to their customers.

4.5.6 Manufacturer's Status

There is no commitment from any manufacturers to follow the ARTU specification at this time. As noted previously, the Carrier 'Centurion' unit had several features of the ARTU including diagnostics.

The Market Connections approach that was initiated prior to the end of the project, was to approach CEE to establish member interest in developing a Voluntary Initiative to promote ARTU features among consumers initially, to build market awareness of the benefits of the ARTU features. Building 'market pull' is thought to be the most direct and effective means of promotion. This will be accomplished through utility education and incentive programs.

The manufacturer for the prototype demonstration was the Carrier Corporation. The unit tested had many of the ARTU features including about 75% of the FDD features. Several additional sensors would be needed to complete the FDD package. This unit from the Carrier PG model line is considered a CEE Tier III unit with the highest EER performance offered by the manufacturer in the 5-7 ton size.

Carrier has already changed its product line to provide gear driven, sealed bearing economizer damper actuators in its factory installed economizer units on all models, not just the high tier models. No other manufacturer has taken this step to make this a standard feature in order to completely avoid the potential for field performance problems and ongoing maintenance requirements. Several manufacturers are noting equipment diagnostic capabilities in their product advertising.

Until the formal development of a CEE Voluntary Initiative by CEE member utilities, manufacturers are unlikely to launch significant efforts to develop an ARTU model. Currently, the manufacturer's R&D facilities are booked until 2010 with the mandated changes in refrigerants and new equipment efficiency levels. There is limited interest in the manufacturers in tackling new product design or promotion outside of existing production.

There will be no need for manufacturers to wait for formal adoption of the specification by standards agencies to produce advanced equipment. Any new equipment produced will certainly meet existing codes and standards and will likely exceed them.

The rollout strategy for advanced RTUs is expected to include promotion at industry trade shows and technical conferences, print advertising in industry publications, local vendor communications with and direct mail to engineers and contractors, etc.

4.5.7 Other Outreach Actions

There are a number of post project activities to be recommended to PIER in the FDD Final Program report.

In the absence of field test data due to the cancellation of the ARTU field test, the strategic decision was made to approach CEE with the option of taking up the ARTU as a Voluntary Initiative for CEE utility members. The approach met with initial success when the CEE HVAC Subcommittee recommended a presentation be made at the annual Industry Partners Meeting in St. Louis in September 2007.

There is an absence of data on the actual performance of higher tier RTUs that already have some of the features of the ARTU. A field research project on assessing how current embedded diagnostics are used in the market is needed. What is the level of market knowledge and interest in diagnostics? Do the HVAC service contractors rely on the diagnostics? How do contractors view diagnostics? What do they think about advanced diagnostics and the potential for web-based user interfaces to report on unit performance?

The CEC adoption of an FDD proposal for the ARTU diagnostic features set in the 2008 Title 24 Nonresidential Building Standards is expected. In the CPUC Strategy previously referenced, one objective calls for incorporating the new 2008 Title 24 FDD Compliance Option provision for unitary HVAC diagnostics as a requirement in the 2011 Title 24 revision. However, a "champion" to promote this new FDD code Compliance provision has to emerge. Hopefully, leadership will come through a combination of utility R&DD activities that include building customer interest.

Additional field demonstrations would be educational and are recommended, but the nature of the product – a long-term increase in reliability, enhanced control, and on-board diagnostics – means that such a demonstration could take years. A demonstration can be envisioned in which the performance of the first generation of installed ARTUs (say, a quantity of 100 – 200) is tracked. This could be done as part of utility initiatives specifically in support of the CPUC Strategy and/or through utility-supported high performance buildings programs. The tracking need not be in the form of continuous monitoring (though several units could be continuously monitored as a control group), but could take the form of an annual survey of unit owners. Owners would be asked to report on how the unit is operating, whether comfort in the space is satisfactory, what the energy usage has been (this might require power transducers and local monitoring), and what routine maintenance has been performed. Especially, owners would be asked whether the ARTU FDD systems have automatically informed them of any problems that developed and how the owners dealt with those problems. For problems that did develop, the energy savings achieved by detecting and fixing the problems immediately, as opposed to having the problem go undetected and the system wasting energy as a result, could be estimated. Problems detected and fixed during installation of the unit would also be noted.

Then, at a point in time several years after the systems are installed, a new report could be issued that reports the survey results. Specifically, the performance of the new ARTUs could be compared to the RTUs surveyed in the original CEC – PIER technical report, "Small HVAC Problems and Potential Savings Reports," October 2003 (P500-03-082-A-25) (also reported in the "Small HVAC System Design Guide," October 2003 (P500-03-082-A12) and elsewhere). The new report should reveal that, compared to these older data, fewer installation problems were allowed to persist, fewer problems occurred during the operation of the units, and of the problems that did occur, the majority were detected, reported automatically to the owner, and resolved in a timely manner. The resulting energy and cost savings achieved by ARTUs would also be publicized, resulting in a real success story for the PIER program.

CHAPTER 5:
Project 5: Rooftop Unit Diagnostics

5.1 Introduction

The work described in this section involved the development, implementation, and deployment of an embedded diagnostic system that is initially being marketed as a field retrofit to existing packaged air conditioning equipment. Existing FDD algorithms were improved and initially evaluated using laboratory data. The embedded system was developed for packaged rooftop air conditioners used in small to medium size commercial buildings. Packaged air conditioners are a good application for embedded diagnostics because they are widely used and tend not to be well maintained. Approximately, 60% of the installed cooling within the U.S. is associated with packaged air conditioners having relatively small individual cooling capacities.

The project was a collaborative effort between Purdue University, Field Diagnostic Services, Inc. (FDSI), and Honeywell, Inc. The development of virtual sensors and improvement of diagnostic algorithms was largely performed by Purdue University. Development of hardware, implementation of diagnostic algorithms, field trials, and development of promotional and training materials was done primarily by FDSI. Honeywell provided technical and financial support for the prototype development and field studies. Additional leverage occurred through a concurrent project that was funded by the Department of Energy.

The technology development section describes the algorithm improvement and evaluation that was performed by Purdue University. The technology implementation and deployment describes product development and field work that was primarily performed by FDSI in cooperation with Honeywell, Inc.

The technology enhancement research includes:

- Research a method for inferring refrigerant pressure using low-cost surface-mounted temperature measurements
- Research on temperature and humidity accuracy in the mixed air chamber relative to the quantity and location of sensors
- Calibrations of a “Smart” sensor capable of measuring the mixed air temperature with a single sensor
- Assess and improve the diagnostic algorithm for economizers
- A method for estimating the optimal time to perform servicing based on operation cost savings and fault service cost

5.1.1 Technology Implementation and Deployment

The ACRx Sentinel is FDSI’s embedded HVAC monitoring and diagnostic product that resulted from this collaborative project. The first production run is coming off the line at the end of 2007 and together with Honeywell, FDSI is working to penetrate the national chain market.

To get to this point FDSI and Honeywell:

- Hired a firm to conduct a marketing study
- Selected a segment of the market and developed product requirements
- Designed the hardware product and refined it over several versions
- Implemented the diagnostic algorithms
- Tested the algorithms with a bench test tool
- Implemented and refined a local technician and remote user interface
- Installed the product in test sites
- Finalized the manufacturing specifications and commissioned the first production run
- Designed a utility program around the product to encourage adoption
- Continue to promote the product as a retrofit to units installed at national chains and OEM factory installations

This report describes the work that has been accomplished in these areas. FDSI is committed to continuing to invest in the enhancement and sale of the Sentinel product.

The challenge moving forward is to bridge the gap between a value proposition the consumer will purchase and the technical capabilities the product provides. This involves developing and demonstrating a management process using supporting technology tools that provides value facility managers will purchase and utilities will incentivize. This exercise helps continue to bring building control system and OEM integration along as these product providers see how the technology can be packaged for consumers to purchase. FDSI is pursuing several specific opportunities with national chains, building control system providers and HVAC OEMs and has partial exclusivity agreements in place.

5.2 Project Objectives

The objective of this project was two-fold: first, to enhance the core diagnostic technology that will process sensor data and evaluate equipment performance second, to use the results to develop a product that provides diagnostic and performance information for rooftop packaged air conditioners. The product allows for condition-based maintenance, remote energy efficiency monitoring, and immediate equipment failure alarms. The product was introduced in California and is unique because no other product provides on-line performance monitoring with enough detail for well-informed remote management.

The technology enhancement section originally had 7 tasks:

Task 5.4.1 Performance Monitoring Indices

Simple indices for evaluating/displaying the performance of the packaged systems will be developed. These indices will measure impact on comfort, efficiency, reliability, control performance, indoor air quality, etc. and will be determined from low-cost measurements.

Task 5.4.2 Refrigeration Cycle Diagnostic Software Implementation

Refrigeration cycle diagnostic algorithms, and enhanced algorithms and performance indices developed in the proposed work will be implemented for on-line application.

Task 5.4.3 Economizer, DCV, and Control System Diagnostics Development

Diagnostic algorithms for 1) economizers, 2) demand control ventilation controllers, 3) internal unit operational controls, and 4) building controls will be developed.

Task 5.4.4 Distributed vs. Centralized Data Processing

An effort will be made to balance distributed versus centralized data processing during product implementation.

Task 5.4.5 User Interface Design

The Service Assistant Online web-based user interface will be generalized to include monitoring data and analysis implemented in this project. An on-site user interface for service technicians will also be implemented and may be PDA-based, like the Service Assistant.

Task 5.4.6 Temperature Sensor Only Refrigeration Cycle Monitoring/Diagnostic Tools

Standard refrigeration cycle diagnostics use two refrigerant pressure sensors. Replacing pressure sensors with external temperature sensors reduces product cost and installation effort. In this task, an effort will be made to eliminate these pressure sensors while maintaining the required accuracy and broad market application of the product.

Task 5.4.7 Improved Decision Making

Faults may be detected and diagnosed well before service is justified. Therefore, it is important to determine proper criteria/thresholds for service. This involves quantifying the impact of different faults on costs and other performance indices that will be used by decision-makers.

The product developed in this project enhanced packaged air conditioning equipment controllers used in commercial buildings. It is based in part on research conducted under PIER Contract 400-99-011. In addition to the controller's normal control functions, the combined system provides diagnostic and performance information. It can be integrated into packaged units with or without economizer and demand-controlled ventilation controllers. The building automation system can provide for data communication and customer access to web-based reports and email alerts quantifying equipment performance and identifying equipment problems needing attention. There is a technician interface at the unit for diagnostic information and immediate feedback on repair effectiveness.

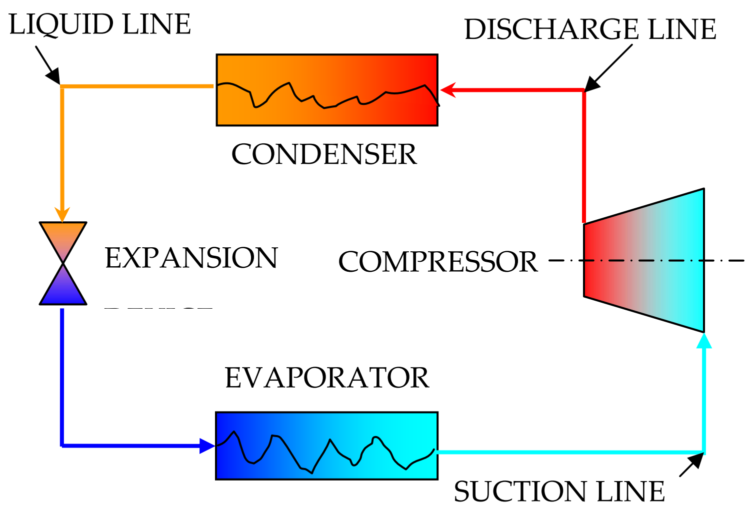
Honeywell is the commercial partner and provided substantial financial support and prospective customers for the pilot demonstration of this new technology. Honeywell is the market leader for packaged unit controls for small commercial buildings and has the resources to successfully market this technology. The intent was to integrate this capability into Honeywell's building controls systems and operation centers.

5.3 Project Approach

5.3.1 Task 5.4.6 Temperature Sensor Only Refrigeration Cycle Monitoring/Diagnostic Tools

Figure 17 illustrates a typical vapor compression system. The system includes four major components: compressor, condenser, expansion device and evaporator. There is also piping between components, including a discharge line between the compressor and condenser, a liquid line connecting the condenser to the expansion device and a suction line between the evaporator and compressor.

Figure 17: Block Diagram for a Typical vVapor Compression System



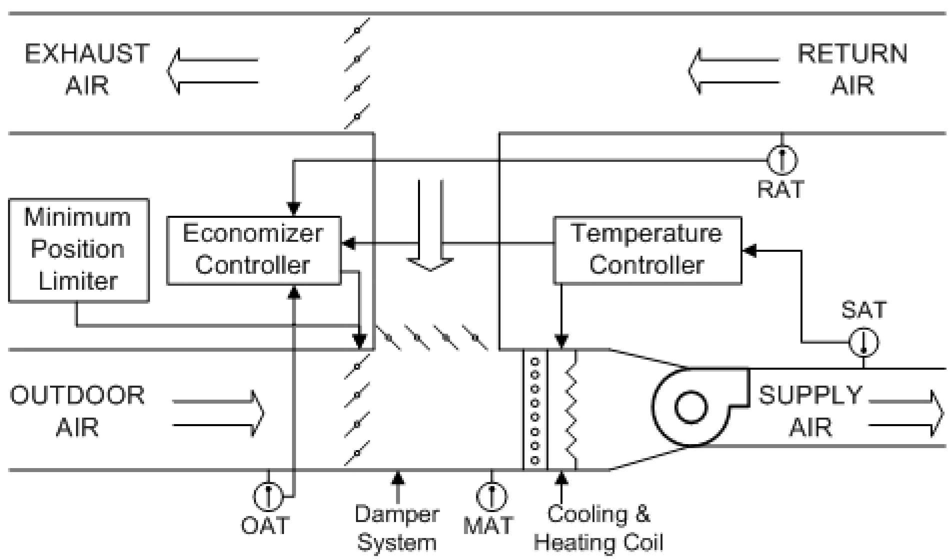
For both the evaporator and condenser, there is typically a portion of each heat exchanger that always contains a two-phase mixture of refrigerant under steady state conditions. Therefore, if a suitable location can be identified and the temperature can be reliably measured then saturation pressures can be inferred from temperature measurements. However, it is necessary to identify appropriate locations within the condenser and evaporator for measuring saturation temperatures and to estimate pressure drops between these locations and other locations where the pressure measurements are needed. Extensive testing was performed within the laboratory to track the location of two-phase sections within the evaporator for a range of operating conditions and levels of refrigerant charge.

Virtual pressure measurements are needed at two places on the high-side of the system: 1) at the compressor discharge for use in characterizing compressor performance and 2) at the outlet of the condenser to determine subcooling for refrigerant charge evaluation.

5.3.2 Task 5.4.3 Economizer Diagnostics

Economizers are incorporated into building HVAC systems to decrease energy consumption during mild weather periods by using outdoor air to meet the cooling load in lieu of the mechanical cooling system. There are two common control strategies for economizer systems: changeover or high-limit control, and differential control (Friedman and Piette, 2001). With changeover control, the ambient dry or wet bulb temperature is compared with an outdoor air setpoint to determine if the economizer should be in "economizer mode." The outdoor state must be sufficiently "cooler" than the expected return air state to ensure that ventilation air will reduce the equipment cooling load. With differential control, the outdoor state (dry or wet bulb temperature) is compared with a measurement of the return air state (dry bulb or wet bulb temperature) to determine if the economizer should be enabled. In economizer mode, the dampers are actively adjusted using a feedback controller to achieve a specified mixed air temperature (MAT) referred to as the mixed air setpoint (MAsetpt).

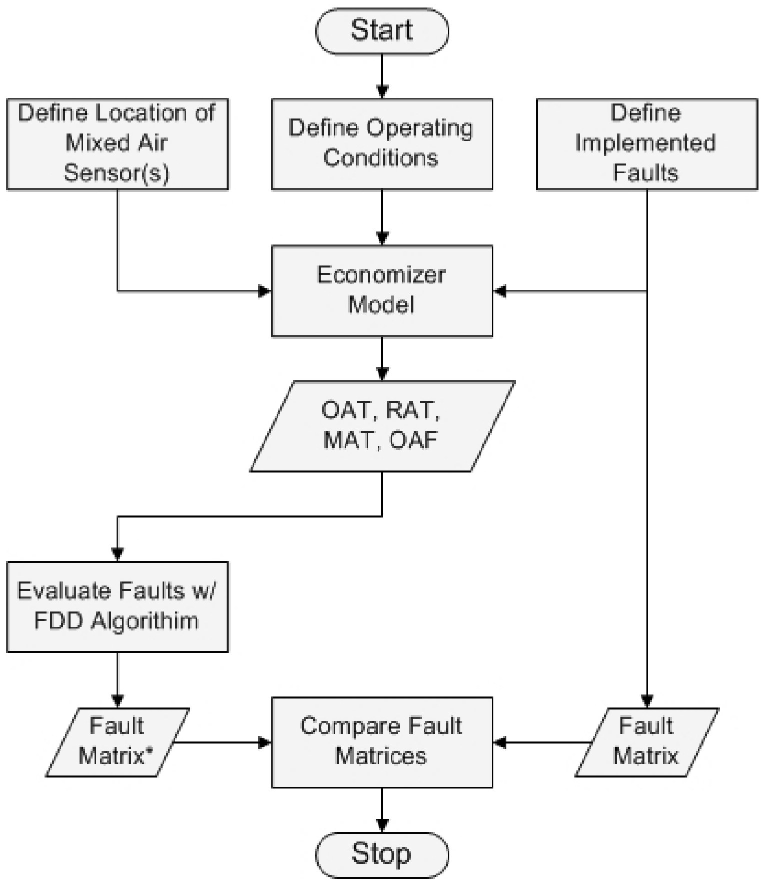
Figure 18: Economizer Schematic



Economizer faults can develop through normal operation or be present due to installation errors. Faults can increase energy costs and/or reduce indoor air quality. For example, a stuck damper that is fully open on a hot summer day leads to increased cooling requirements and costs. On the other hand, a stuck damper that is fully closed can degrade IAQ leading to decreased worker productivity and higher business costs.

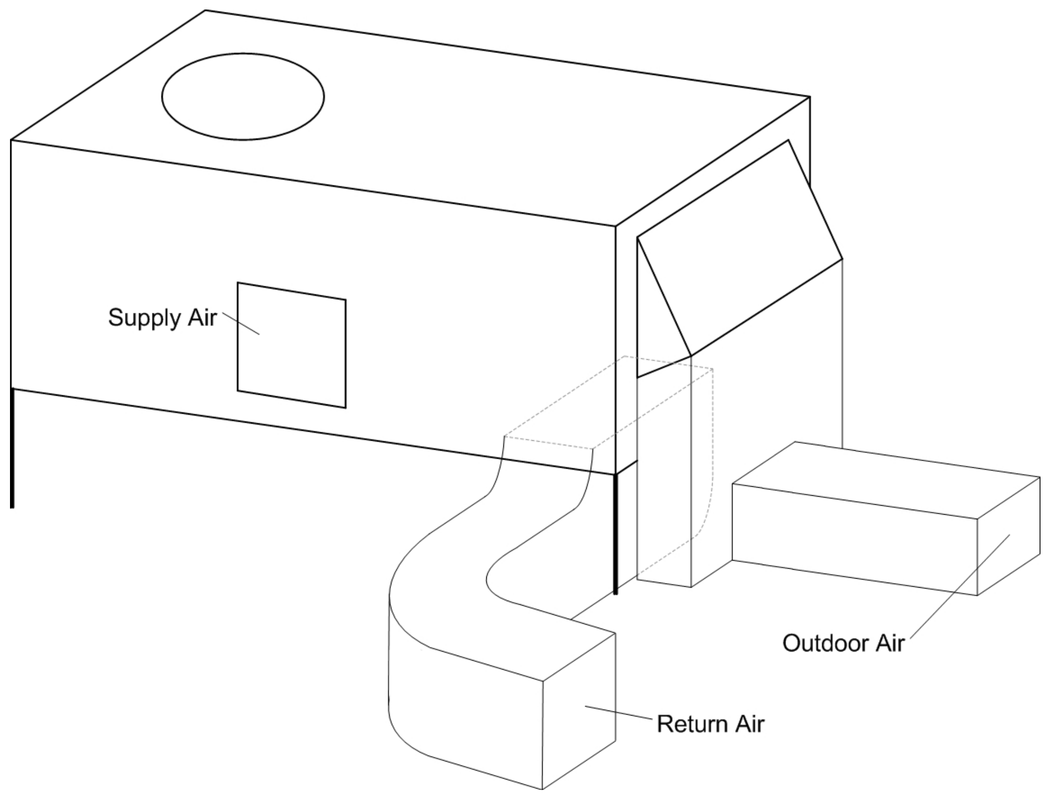
Detailed temperature and humidity profiles for mixed air were collected over a wide range of damper positions, supply air flow rates, and ambient air conditions. These data were then used to develop empirical models that could predict average mixed air temperatures and humidities as a function of 1) number of sensors and location, 2) damper position, 3) ambient temperature and humidity, and 4) return air temperature and humidity. These models were then integrated with a model of the economizer controller and fault models in order to evaluate diagnostic algorithm performance. Figure 19: Diagnostic Algorithm Evaluation Process Flowchart depicts the evaluation process. The operating conditions, faults to be simulated, and number and location of mixed air sensors are specified as inputs. This information is used within the economizer system model to predict sensor outputs for outdoor air temperature (OAT), return air temperature (RAT), mixed air temperature (MAT) and the outdoor air fraction (OAF) which are all inputs to the diagnostic algorithm. The economizer diagnostic algorithm was evaluated for eight different faults with four different combinations of mixed air sensors for both dry-bulb changeover and differential dry bulb control.

Figure 19: Diagnostic Algorithm Evaluation Process Flowchart



The experiments were performed on a Trane 5-ton rooftop unit (model number TSC060A) equipped with an economizer (model number BAYECON085A). The economizer used in this setup was designed to be packaged and controlled in combination with the mechanical cooling system, which is termed an integrated system. The rooftop unit was setup inside a psychrometric chamber at the Herrick Laboratories, Purdue University, to simulate outdoor conditions. A diagram of the experimental setup is shown in Figure 20: Economizer Experiment Ducts Setup (not to scale). The unit was elevated off the floor so that return air ducts could be attached under the unit and then connected to another psychrometric chamber that simulated indoor conditions. A duct was attached to the outdoor air inlet to the economizer for measurement purposes. The indoor supply duct from the rooftop unit was connected to an air flow measurement system that contained calibrated flow nozzles. In addition to the installed rooftop indoor fan, an external variable fan was utilized to overcome pressure drop in the air measurement system and achieve the range of required flow rates.

Figure 20: Economizer Experiment Ducts Setup (not to scale)



To set up a test, the indoor and outdoor psychrometric chambers were utilized to control the temperature and relative humidity (RH) for the outdoor and return air streams. With the chambers active and at steady state conditions and the fans set to the required air flow rate, the economizer damper position could be varied over its entire range. For each condition and damper position, temperature data were collected continuously. Initial tests reveal that the outdoor air fraction (OAF) varies linearly with the damper position and therefore it was only necessary to consider four damper positions.

A test matrix was developed to consider a wide range of damper positions for both heating and cooling operating conditions. The first set of tests conducted were the tests in heating mode at 20°F, 30°F, and 40°F OAT and 70°F RAT for three different air flow rates. Through this testing, it was verified that the mixed air conditions were nearly independent of the supply air flow rate for a given damper position. It was deemed unnecessary to conduct cooling mode tests at different air flow rates and 2000 CFM flow rate was used for tests in cooling mode.

Once the testing was completed the next step was to develop a model. This section presents the approach of the economizer model, fault implementation, and sensor combinations.

The economizer model contains three parts: 1) a mapping between mixed air temperature and damper position, outdoor conditions, and return conditions, 2) an economizer controller model, and 3) a fault implementer. Models were developed in order to predict the "sensed" mixed air temperature for different choices for number and location of sensors in terms of outdoor air fraction and temperature and return air temperature.

The fault implementer allows for single or multiple economizer faults. The most common faults are associated with the damper. Additional faults associated with sensors and controllers were also considered in this study. Eight individual faults were evaluated and categorized in Table 8: Economizer Categorized Fault List.

Table 8: Economizer Categorized Fault List

Fault Category	Fault Name
Sensor Faults	Temperature Sensor Bias
Sensor Faults	Bad Sensor
Sensor Faults	Misplaced Sensor
Controller Faults	Incorrect MAT Setpoint
Controller Faults	Incorrect Minimum OAF Setpoint
Damper Motor/Actuator Faults	Damper Motor Failure (OAF=0)
Damper Motor/Actuator Faults	Lack of Control Signal to Damper (OAF=minOAF)
Damper Motor/Actuator Faults	Physically Stuck Damper (OAF=constant)

The sensor bias represents an improperly working sensor and was implemented as a specified fixed error. The bad sensor fault represents a total sensor failure and was simulated by setting the sensor output to an artificially high number. The misplaced sensor refers to a sensor that is wired to the wrong channel and was simulated by considering different combinations where the two channels are reading the same value (e.g., the OAT channel reading the RAT). Six combinations of misplaced sensors were considered including replacing the OAT with the RAT and MAT, the RAT with the OAT and MAT, and the MAT with the OAT and RAT. The incorrect setpoints (faults 4, and 5) were simulated by specifying a fixed bias and represent faults where the economizer system controller setpoints and the setpoints supplied to the FDD algorithm are not the same. These controller faults also could represent problems more physical in nature such as a damper motor potentiometer specifying the minOAF is not set properly. The damper/actuator faults (faults 6, 7, and 8) were implemented by specifying a fixed damper position.

The original diagnostic algorithm was designed to detect problems with an economizer and an air handling unit (AHU) control system. The algorithm monitors OAT, RAT, and MAT and then estimates OAF from a mass/energy balance. This information is used for economizer diagnostics. In addition, the system monitors the AHU's SAT, thermostat call for cooling or heating, demand control ventilation, and indoor airflow status. Also, the algorithm has built in occurrence criteria so that a fault must be present for a certain period of time for it to be detected. The experimental data could only be used for detecting a portion of potential faults related to the economizer only. Also, it is assumed that the economizer system simulated by the model is in steady state and therefore, all of the occurrence criteria in the algorithm were not observed.

The algorithm provided was reduced to the fault detection logic that could be evaluated using the economizer model. The portions of the logic that had time-based elements associated with them were removed. For example, the OAF involved an error calculation which compounded temperature measurement error over time. This error calculation was removed and approximated by assuming an error of 0.02 F for the OAF. This error is abbreviated as DOAF. Seven of the algorithm's faults were used and are listed below in

The OAF logic in Figure 21 returns an "invalid OAF" if the OAF is calculated to be below zero or above one and an "undetermined OAF" if the outdoor and return air temperatures are too close together. The determination of OAF is performed after the criteria for "no economizer cooling at low OAT" because it is not required until after the first four fault criteria are checked.

Figure 21: Logic to Determine the OAF

```
if OAT-RAT>=10
      OAF=(MAT-RAT)/(OAT-RAT)
      if OAF<0 and OAF>=1
         OAF='Invalid OAF'
   elseif OAT-RAT<=-5
      OAF=(MAT-RAT)/(OAT-RAT)
      if OAF<0 and OAF>=-1
         OAF='Invalid OAF'
   else
      OAF=(MAT-RAT)/(OAT-RAT)
      if OAF<0
         OAF='Invalid OAF'
      else
         OAF='Undetermined OAF'
```

Table 9: Fault Criteria of the Provided Algorithm (All temperatures in °F)

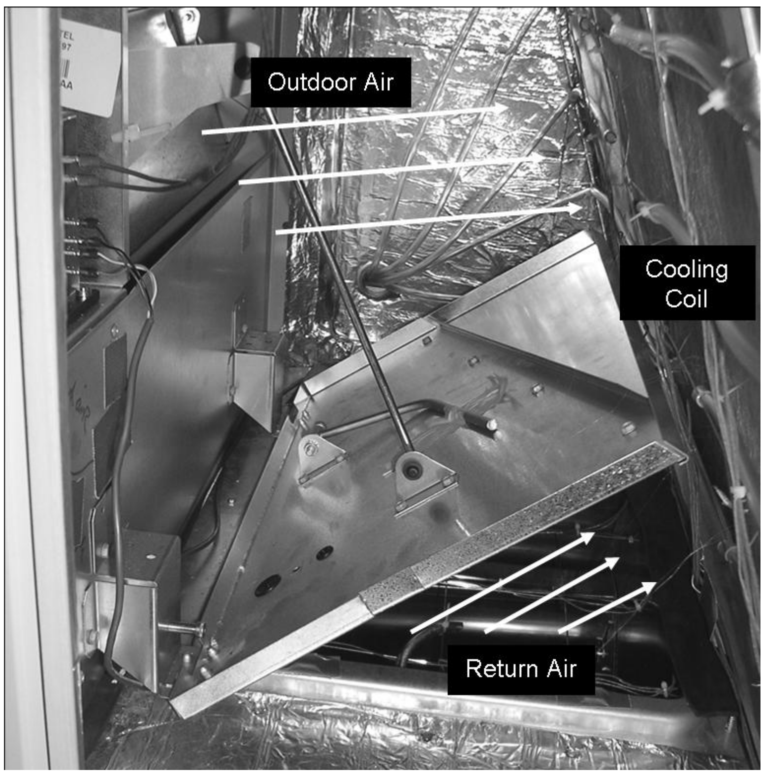
Fault	Fault Criteria
OAT out of range	OAT<-15 or OAT>125
RAT out of range	RAT<(65-1) or RAT>(85+1)
MAT out of range	if MAT-RAT>=-2 and MAT-RAT<=1 if MAT<(OAT-2.5) and MAT<(RAT-2.5) or MAT>(OAT+2.5) and MAT>(RAT+2.5) else if if MAT<(OAT-5) and MAT<(RAT-5) or MAT>(OAT+5) and MAT>(RAT+5)
No Economizer Cooling at Low OAT	OAT-RAT<-5 & OAT>45 & MAT-RAT>-5
High OAF When High OAT	OAT-RAT>5 & OAF is valid & OAF-DOAF>2*min_OAF
Low OAF During Occupied Period	OAF+DOAF<minOAF
Low Mixed Air Temperature	MAT<40

5.3.3 Smart Mixed Air Temperature Sensor

Diagnostic methods for economizer systems and air conditioning equipment require accurate measurements of mixed air temperature (MAT). However, packaged air conditioner equipment for small commercial applications typically have small chambers for mixing outdoor and return air and can have a very non-uniform temperature and velocity distributions at the inlet to the evaporator. Furthermore, the mixing process can change significantly as the position of the dampers changes with economizer operation. Wichman (2007) demonstrated that at least four temperature sensors mounted symmetrically about the duct centerline are necessary to achieve good accuracy for mixed air temperature. Fortunately, a single moisture sensor located at the duct center is sufficient.

The requirement for four mixed air sensors adds significant cost to a diagnostic system. This section describes the development and evaluation of a smart mixed air temperature sensor that utilizes a single mixed air temperature and other available measurements to correct for a non-uniform temperature distribution. The method was evaluated using data obtained for a typical small commercial rooftop air conditioner employing an air-side economizer. The rooftop unit was set up inside environmental chambers to simulate indoor and outdoor conditions. The evaporator coil is located in very close proximity to the outdoor and return air dampers and the air intakes are not symmetrical leading to very poor mixing. An array of 15 temperature sensors was mounted at the filter inlet. Air flow rates were measured for the outdoor and return air steams.

Figure 22: Economizer Air Mixing Chamber, Arrows Demonstrating Air Flow Direction

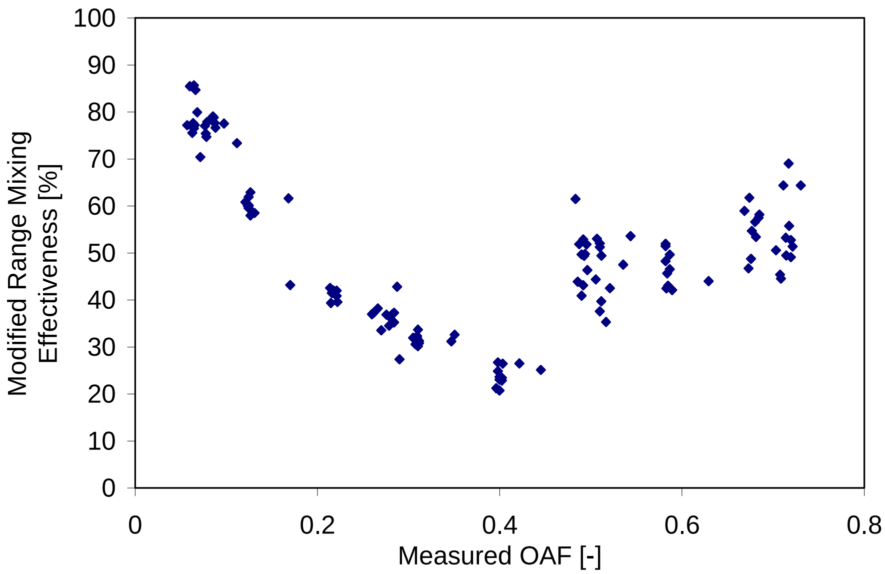


The poor mixing arrangement can be quantified using the modified range mixing effectiveness defined by Robinson (2000) as

$$E_{RdT} = \left(1 - \frac{T_{\max} - T_{\min}}{|OAT - RAT|}\right) \times 100\%$$

where T_{max} and T_{min} are the maximum and minimum measured MATs from the mixed air measurement grid, OAT is outdoor air temperature and RAT is return air temperature. This mixing effectiveness has a range of 0-100% where 100% represents ideal mixing. E_{RdT} was calculated for a wide range of damper conditions and ambient temperatures and is plotted as a function of the outdoor air fraction (OAF) in Figure 23: Modified Range Mixing Effectiveness as a Function of Outdoor Air Fraction. Outdoor air fraction is the ratio of outdoor air flow rate to the total air flow supplied by the rooftop air conditioner.

Figure 23: Modified Range Mixing Effectiveness as a Function of Outdoor Air Fraction



The modified range mixing effectiveness is at a minimum of about 25% around 0.4 OAF. This poor mixing effectiveness can be attributed to the small size of the mixing chamber and large return air damper that prevents the outdoor and return air flows from mixing before reaching the evaporator coil. Based on these experiments, a typical air mixing chamber does not uniformly distribute outdoor and return air making it difficult to get an accurate measurement of MAT.

The goal is to correct a single-point MAT measurement to account for non-uniform temperature distributions. This method utilizes a combination of available temperature sensors (return, outdoor, mixed, and supply air) and the equation

$$OAF = \frac{MAT - RAT}{OAT - RAT}$$

to estimate the bias error in the MAT. The MAT bias error could be estimated automatically during a self-calibration mode. During this self-calibration, the compressor would be turned off and the damper would cycle through various positions and collect temperature data. Over time, a wide range of temperature data could be collected with different OATs and RATs. The MAT bias error could then be correlated with the damper control signal, OAT, and RAT to account for effects of the imperfect mixing process.

In the experiments used to evaluate the method, the temperatures of the outdoor and return air streams were varied along with the damper position to measure the mixed air temperature distribution across the evaporator. The method for developing this correlation was performed three times using the most accurate one, two, and four point MAT sensor combinations. The error in a single-point measurement of MAT was evaluated as

$$MAT_{error} = MAT_{1pt} - MAT_{baseline}.$$

where MAT_{1pt} was measured at the centerline of the duct at the inlet to the evaporator filter and $MAT_{baseline}$ is based off a SAT corrected for $\Delta T_{fan.}$ For the purpose of characterizing damper position, a normalized damper control signal (γ_D) was determined, with γ_D=0 being maximum return air and γ_D=1 being maximum outside air. Following are the resultant MAT_{error} as a function of damper position.

Figure 24: Single-Point MAT_{error} as a Function of γ_D

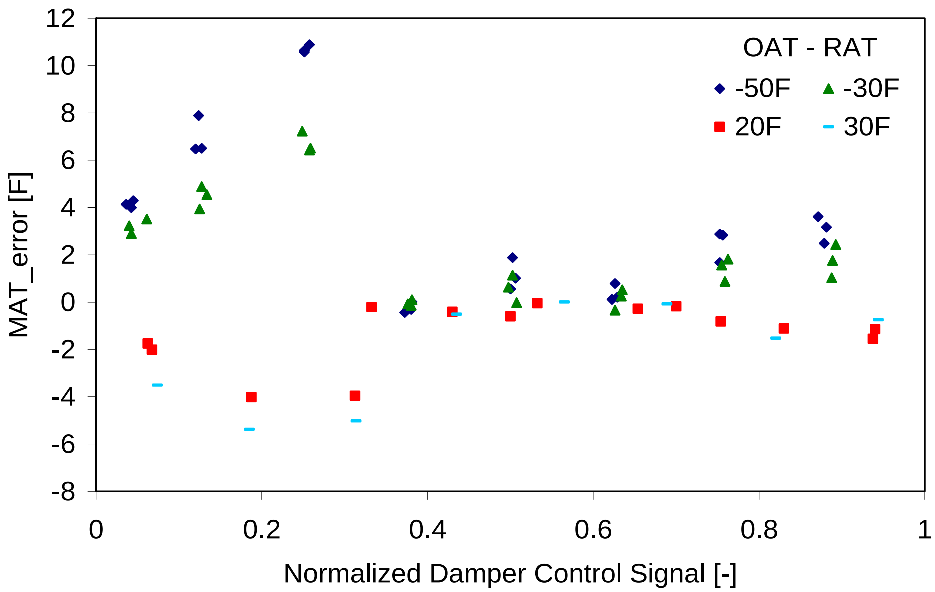


Figure 25: Two-Point MAT_{error} as a function of γ_D

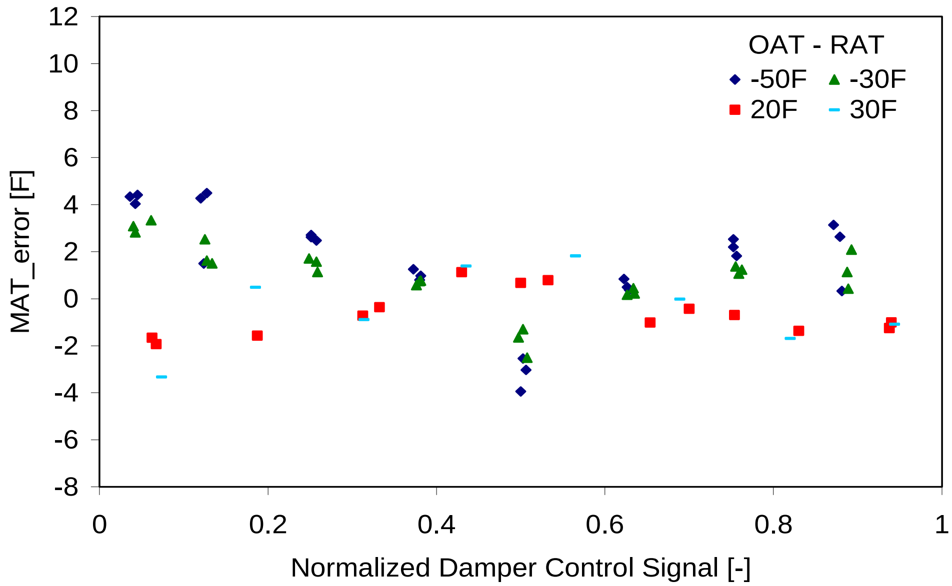
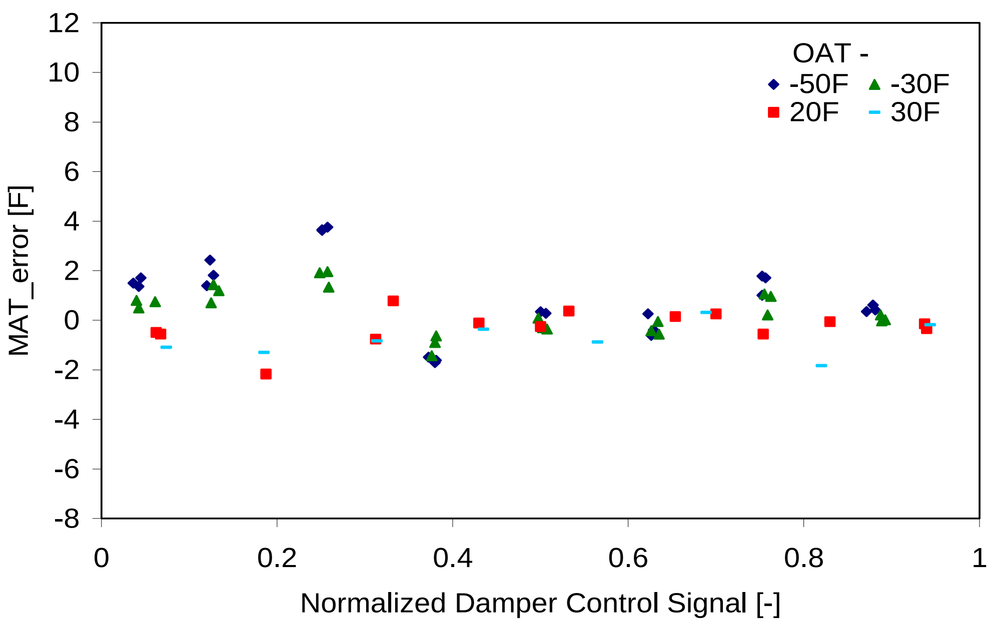


Figure 26: Four-Point MAT_{error} as a Function of γ_D

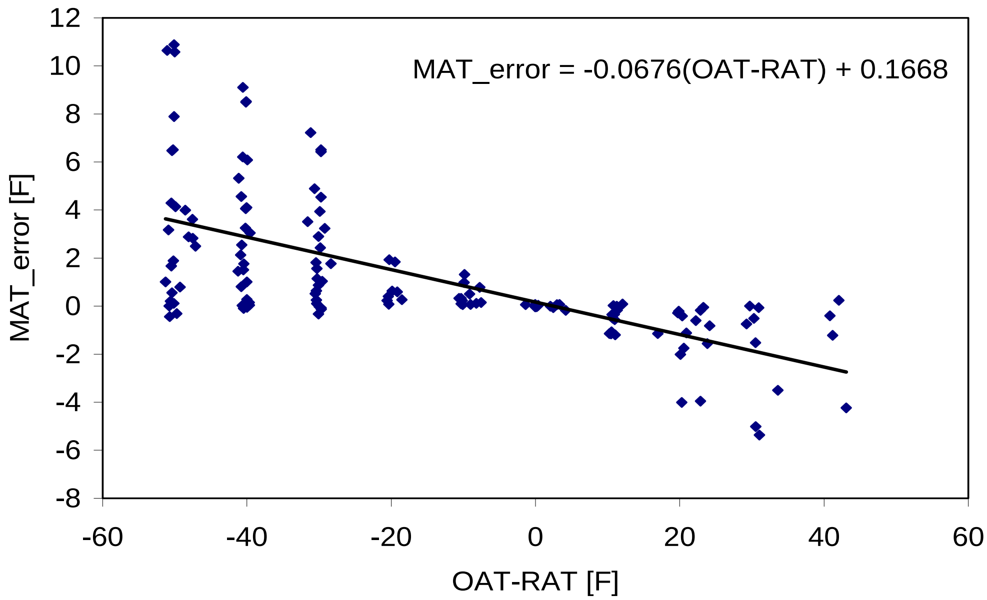


The correlation between the MAT_{error} and the normalized damper control signal is very nonlinear when a single-point measurement is employed. As a starting point, the effect of damper position is not considered and the MAT_{error} is correlated as a linear function of the difference between OAT and RAT according to

$$MAT_{error} = \alpha(OAT - RAT) + \beta \qquad \text{(Equation 1)}$$

Figure 27 shows the single-point MAT_{error} as a function of the difference between the OAT and RAT along with a linear relationship that provides the best fit to the data.

Figure 27: Single-point MAT_{error} as a Function of the Difference between OAT and RAT



Although there is a lot of scatter, this model for the error can be used to correct a single-point MAT measurement using

$$MAT_{corrected} = MAT_{1pt} - MAT_{error,predicted}$$

Incorporating the damper position into the correlation is difficult because it has a highly non-linear effect. Simple analytical functions cannot capture the nonlinearity. However, it is feasible to use the simple linear correlation function of Equation 1 and apply it to MAT_{error} data according to individual bins associated with damper position (γ_D). Separate linear correlations based on the difference between the OAT and RAT are developed for each range of γ_D. This approach allows characterization of the highly nonlinear damper dependence but requires that data be collected over a range of ambient temperatures.

The economizer data was divided into ten equally sized bins according to damper position. The normalized damper control signal had a range of 0.1 for each bin. Separate linear correlations were created for each bin from the economizer data. Figure 28 and Figure 29 show typical results for two of the damper bins. In general, the single-point MAT error correlates very well with damper position and the difference between OAT and RAT.

Figure 28: Single-Point MAT_{error} as a Function of the Difference between OAT and RAT for γ_D in the Range of 0-0.1.

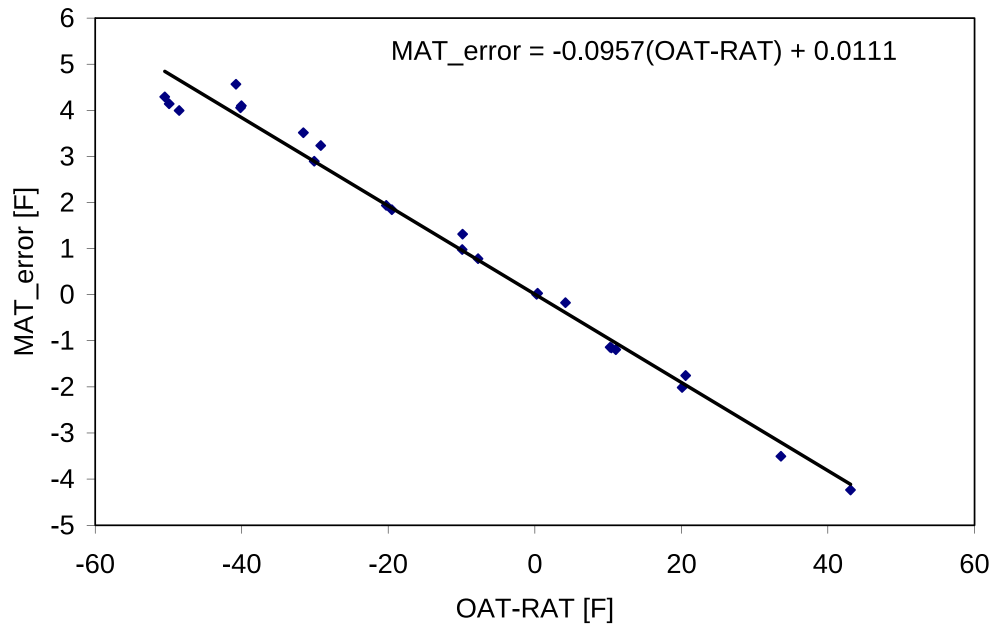
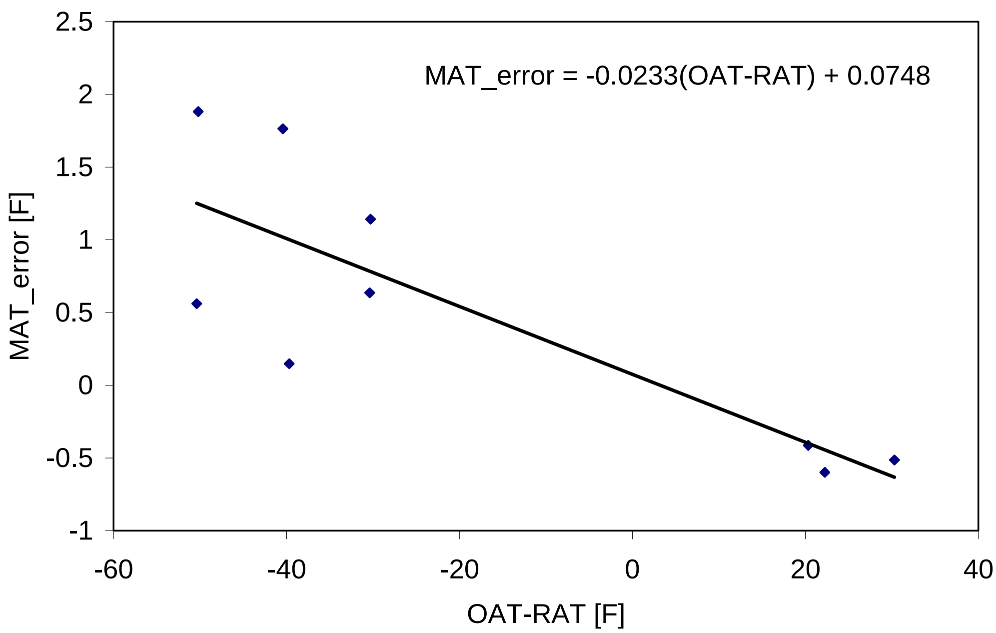


Figure 29: Single-Point MAT$_{error}$ as a Function of the Difference between OAT and RAT for γ_D in the Range of 0.4-0.5.



5.3.4 Fault Evaluation and Decision Making

Only a very limited number of publications have addressed service scheduling associated with automated fault detection and diagnostics (FDD) applied to air conditioning equipment. Krafthefer et al. (1987) demonstrated the cost effectiveness of using high efficiency air cleaners instead of more commonly used dust stop filters in heat pumps to maintain coil cleanliness. Rossi and Braun (1996) developed a near-optimal service scheduling algorithm for the cleaning of heat exchangers in air conditioning equipment and demonstrated that there is a significant opportunity for cost savings associated with optimal scheduling of condenser and evaporator maintenance.

To develop an optimal service scheduling for any fault, a method for evaluating faults needs to consider two issues: 1) how to evaluate the consequences of faults and 2) how to estimate the service costs. The primary consequences of faults in HVAC systems are comfort-related, environmental and economic instead of safety-critical. Impacts of faults on comfort and environment are relatively straightforward to evaluate with an automated FDD system, while economic impacts are complicated. Li and Braun (2007a) investigated possible factors that impact economic performance and defined an overall economic performance degradation index ($EPDI$). For completeness, the first part of this section briefly describes $EPDI$ and an economic performance degradation evaluation method using $EPDI$. The second part of this report addresses how to assess service costs.

Based on the economic performance degradation evaluation and service cost estimation methods, fault evaluation and decision are investigated in the third part of this section. Fault evaluation and decision are two important steps for non-critical FDD applications. Rossi and Braun (1997) suggested four evaluation criteria for faults in air conditioning equipment: comfort, economics, safety, and environment. The environmental criteria refer to refrigerant leakage, whereas in this application, safety refers to the safety of the equipment. If refrigerant leakage or faults that compromise equipment safety are detected (e.g., liquid slugging), then they should be fixed. Similarly, if the cooling capacity of the unit has degraded sufficiently that comfort could be comprised at some point then the unit should also be repaired. The economic criteria are more complicated to evaluate and are the focus of this section. Similarly, Rossi and Braun (1997) proposed four fault decisions: tolerate, repair ASAP, adapt control, and stop to repair. A 'stop to repair' decision would result from any fault that was severely impacting comfort or equipment safety. However, this decision is not specifically addressed in the current work. An additional decision, termed 'repair at low season', is added to address the cost advantages of better service scheduling. The fault evaluation and decision methods are essentially an optimization problem for minimizing the total costs of operation and service. In order to reduce the computation complexity, an optimal service searching algorithm is proposed. Finally, validation of the proposed methods is described.

5.3.5 Economic Performance Degradation Evaluation Method

Many systems are affected by faults that are not detected during preventive maintenance inspections. These undetected faults result in significant system performance degradations. Li and Braun (2007a) considered the following factors which affect the economics of air conditioning: 1) EER or COP, which quantifies the energy performance of the refrigeration system and a degradation directly raises the operating costs; 2) cooling capacity ($\dot{Q}_{cap}$), whose degradation can impact comfort in the conditioned space and can also reduce the equipment life due to longer compressor runtime for the same load and greater wear of active components; 3) sensible heat ratio (SHR), which can decrease with many faults leading to higher total equipment load and greater energy consumption for the same sensible building load. In order to consider the impact of these effects on operating costs, an overall economic performance degradation index, termed EPDI, is defined. EPDI can be used to be used within an FDD system to evaluate operation cost savings associated with repairing diagnosed faults and can be used to assess the economic benefits associated with application of FDD. For the purpose of evaluating operation cost savings, EPDI is calculated as:

$$EPDI = \frac{1}{1-r_{\Delta SHR}}\left(\frac{1}{1-r_{\Delta EER}}\frac{\bar{C}_{utility}}{\bar{C}_{utility}+\bar{C}_{equip}}+\frac{1}{1-r_{\Delta cap}}\frac{r_{equip}\bar{C}_{equip}}{\bar{C}_{utility}+\bar{C}_{equip}}\right)-1$$

where $r_{\Delta SHR}$, $r_{\Delta EER}$ and $r_{\Delta cap}$ are defined as degradations in SHR, EER and $\dot{Q}_{cap}$, respectively, resulting from diagnosed faults, $\bar{C}_{equip}$ is the average price for equipment capital costs, initial installation costs and maintenance and service cost for normal operation, and r_{equip} is the ratio of $\bar{C}_{equip}$ for faulty operation to the normal value. The term $\bar{C}_{utility} = \bar{\dot{W}}_{normal}\bar{C}_{electricity}$ is the average utility cost for normal operation where $\bar{\dot{W}}_{normal}$ is average power consumption for normal operation and $\bar{C}_{electricity}$ is the average cost per unit of electricity.

$EPDI$ relates performance degradation parameters for the air conditioning equipment due to faults to the net increase of normalized total costs associated with maintaining a conditioned space. The operating cost saving associated with repairing the diagnosed faults can be estimated as,

$$OCS = EPDI \times (\bar{C}_{utility} + \bar{C}_{equip}) \times T_{diag-rep}$$

where $T_{diag-rep}$ is the time span from the point of diagnosing to the time of repairing the diagnosed faults. The larger the $EPDI$, the more severe the faults and the greater the performance degradation. The operating cost saving associated with repairing the diagnosed faults also depends on the baseline for the total operating costs.

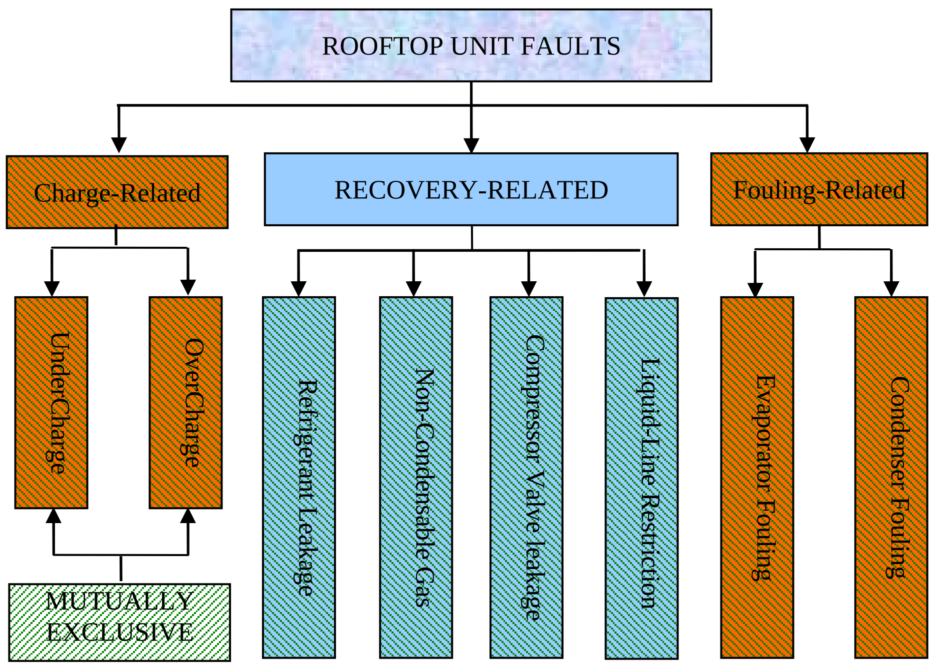
5.3.6 Service Cost Estimation Method

With application of automated FDD, service is performed in a more efficient manner resulting in service cost savings. Estimation of service cost for faults considered for repair has two applications: 1) prior economic service justification for those faults that do not violate criteria, such as comfort or environmental, that would lead to immediate service; 2) posterior calculation of the payback period for all the faults that have been identified for service. The first application involves fault evaluation and decision making and requires iterative evaluation of service costs for different fault combinations until a final fault decision that leads to maximum net savings is made. However, the second application is informational and is a simple one-time calculation when a final fault decision has been made. In spite of these two applications, the method is presented in a generic way, with specific attention to the two specific applications where necessary.

5.3.7 Taxonomy of Faults Based on Service

Before deriving a methodology for estimating service costs, RTU faults considered in this study are categorized from the service point of view (see Figure 30). Rooftop unit faults can be divided into recovery-related, charge-related and fouling-related faults. Recovery-related faults (RRF) require a time-consuming recovery procedure, and include refrigerant leakage, non-condensable gas, liquid-line restriction and compressor leakage faults. Charge-related faults (CRF) consist of overcharge and undercharge. With the help of automated FDD, charge-related faults do not require a leakage check for diagnosis and a recovery procedure for repair. In addition, the two CRFs are mutually exclusive, i.e., they cannot occur simultaneously. Fouling-related faults (FRF) include condenser and evaporator fouling faults, which require a short service time but a costly base visit fee if scheduled individually. Another characteristic is that FRFs occur periodically rather than randomly.

Figure 30: Taxonomy of RTU Faults for Service Purposes



5.3.8 Estimation of Service Costs

Service costs (SC) are the sum of hardware replacement costs (HC) plus labor costs (LC),

$$SC = HC + LC .$$

Except for compressor faults, parts replacement costs are not considered because compared with service costs, the costs of most HVAC disposable parts such as filters are negligible. A liquid line filter/drier costs around \$15, while the labor fee for replacement costs about \$300. An evaporator filter costs around $2, while the labor fee for replacement costs $30. Refrigerant R-22 costs less than $2/lb, while leak checking plus recharging costs more than $400.

According to our survey of service technicians, the labor costs, LC, are typically charged at a fixed base visit fee plus a time-based labor fee,

$$LC = BC + C_{hourly}T_{service}.$$

where BC is a fixed base visit fee, C_{hourly} is the hourly rate, and $T_{service}$ is the service time (hour). Both BC and C_{hourly} vary with location and service company, but typically BC is around $115/visit and C_{hourly} is about $65/hour.

Table 10 tabulates estimated service times and costs for individual faults that are expected for application of automated FDD. Automated FDD allows the elimination of time-consuming diagnoses for all faults and the elimination of the system recovery task for charge-related faults. The base fee accounts for a large percentage of the total costs.

Besides eliminating diagnoses, automated FDD is capable of scheduling potential multiple-fault services for single and/or multiple units at a site. Multiple services significantly reduce service costs by reducing the base fee percentage for each individual fault and improving productivity in the following aspects:

1) Some tasks can be performed simultaneously. Since most of the service time for recovery-related faults is spent on the recovery procedure, they are mutually inclusive. This means that the service time spent on multiple recovery-related faults can be considered as the time spent on the fault with the longest service time. Charge related and non-condensable gas faults can be fixed without additional effort when replacing the filter/drier or compressor.
2) Dead time for one task can be used to do other tasks. For example, an evaporator filter can be replaced and a condenser coil can be cleaned while the system is being recovered. So service cost estimation should be based on multiple services.

Table 10: Typical Service Times and Hardware Costs for Individual Faults with the Help of Automated FDD

Fault Name	Category	HC ($/ton)	BC ($/visit)	$T_{service}$ (hour)	LC ($)
Compnv	RRF	85	115	5	440
Llrestr		0	115	5	440
Noncond		0	115	3.5	343
Refleak	RRF	0	115	4	375
Refunder	CRF	0	115	1	180
Refover		0	115	1	180
Condfoul	FRF	0	115	0.5	147
Evapfoul		0	115	0.5	147

If there is no RRF ($k_i = 0$), no service time is required for $RRFs$ and no service time is available for "absorbing" the service time of other $RTUs$,

$$T_{RRF,i} = T_{supply,i} = 0,$$

and the service time is

$$T_{demand,i} = \sum_{j=1}^{m_i} T_{service,j}.$$

If there are any $RRFs$ ($k_i \neq 0$), the total service time for $RRFs$ on unit i, $T_{RRF,i}$, would be the maximum service time for servicing an individual recovery-related fault,

$$T_{RRF,i} = \underset{j=1}{\overset{k_i}{Max}}(T_{service,RRF_j}),$$

and all of the service time for other faults on this unit can be absorbed,

$$T_{demand,i} = 0.$$

Since $RRFs$ can allow two hours of dead time to absorb other service times, there may be some time left to absorb more for other $RTUs$. If there are no $CRFs$, then

$$T_{supply,i} = 2 - 0.5(m_i - k_i).$$

If there are any $CRFs$,

$$T_{supply,i} = 2 - 0.5(m_i - k_i - 1),$$

If only the unit i is considered for repair, the total service time of RTU_i would be

$$T_{RTU,i} = T_{RRF,i} + Max(T_{demand,i} - T_{supply,i}, 0).$$

The service cost is related to the type of fault decision. For faults that impact comfort (i.e., significant capacity degradation) or the environment (i.e., refrigerant leakage), service should be performed ASAP without any economic consideration. The fact that these faults need to be serviced quickly affects the service costs for other faults being evaluated based upon economic considerations. For example, if a refrigerant leakage fault was detected, service should be performed ASAP without any economic consideration, but two hours of deadtime could be "free" for use by other non-RRFs occurring simultaneously with it. This "free" time is termed $T_{service,free}$, and it is 1) brought by those RRFs which violate comfort and/or environmental criteria and 2) available for non-RRFs only if they are serviced ASAP. Similarly, BC_{free} is a "free" base visit fee that has been paid for by the service of any faults which violate comfort and/or environmental criteria. The difference between $T_{service,free}$ and T_{supply} is that $T_{service,free}$ is free service time that has been justified by comfort and/or environmental criteria, whereas T_{supply} is free service time that could be available if the fault under consideration is justified by economic criteria.

The total labor costs should be based on a site analysis. The service for multiple units reduces labor costs because of 1) a shared base fee, 2) the application of dead time, and 3) possible "free" service time and/or "free" base fee. For faults that do not violate comfort and/or environmental criteria, a service decision is made based on economic criteria, i.e., to determine a fault combination for servicing that would lead to the maximum net savings. Before fault decisions are made, service for the considered faults could be either 1) performed ASAP (possibly with those faults violating comfort and/or environmental criteria) or 2) performed later and therefore postponed to the low season where labor is less costly. Corresponding to the above two possible service options, $T_{site,asap}$ and $T_{site,low}$ are defined to quantify the service time for service performed ASAP and during low season, respectively.

The total service time associated with a site visit caused by a need for immediate (ASAP) service is calculated as

$$T_{site,asap} = \sum_{i=1}^{n} T_{RRF,i} + Max\left(\left(\sum_{i=1}^{n} T_{demand,i} - \sum_{i=1}^{n} T_{supply,i} - T_{service,free}\right),\ 0\right),$$

which is a sum of RRF service times for each unit ($\sum_{i=1}^{n} T_{RRF,i}$) and the non-negative value of the difference between the sum of service time demand of each unit ($\sum_{i=1}^{n} T_{demand,i}$) and the sum of service time supply of each unit ($\sum_{i=1}^{n} T_{supply,i}$) minus $T_{service,free}$.

The total service time associated with a site visit during low season is calculated as

$$T_{site,low} = \sum_{i=1}^{n} T_{RRF,i} + Max((\sum_{i=1}^{n} T_{demand,i} - \sum_{i=1}^{n} T_{supply,i}), \ \ 0).$$

Compared with $T_{site,asap}$, $T_{site,low}$ cannot use $T_{service,free}$ because $T_{service,free}$ is only available for service performed ASAP that was not based on economic criteria.

The service costs associated with these two types of site visits are determined as

$$SC_{site,asap} = \sum_{i=1}^{n}\sum_{j=1}^{m_i} HC_j + (BC - BC_{free}) + C_{hourly} T_{site,asap}.$$

$$SC_{site,low} = \sum_{i=1}^{n}\sum_{j=1}^{m_i} HC_j + \alpha_{discount} C_{hourly} T_{site,low}.$$

where $\alpha_{discount}$ is a discount factor for labor fees in the low season. The base visit cost, BC, does not appear in the low season service costs because it would be scheduled with the preventive maintenance inspection which is assumed to be performed once a year at low season.

5.3.9 Fault Evaluation

If refrigerant leakage or faults that compromise equipment safety are detected (e.g., liquid slugging), then they should be fixed. Similarly, if the cooling capacity of the unit has degraded sufficiently that comfort could be compromised at some point then the unit should also be repaired. The economic criteria are more complicated to evaluate and is the focus of this section.

The potential operating cost savings associated with repair of a diagnosed fault are a function of 1) $EPDI$, 2) normal operating costs of the affected unit OC_{normal}, and 3) the remaining runtime from the current time to the next service time, termed T_{RRT}.

$EPDI$ and OC_{normal} can be calculated when a fault is diagnosed. T_{RRT} can be calculated according to fault type. Fouling faults occur regularly and even periodically and it is assumed that they will be repaired during a preventive routine inspection scheduled for low season. T_{RRT} for fouling faults is then the remaining seasonal runtime, from the current time to the low season, termed T_{SRRT}. All faults of all the units at the same site have the same T_{SRRT}. With the application of automated FDD, refrigerant under charge and over charge only require short service times and could also be repaired in the low season during the yearly preventive maintenance inspection visit. For any recovery-related faults, T_{RRT} is assumed to be the remaining life runtime, termed T_{LRRT}. Different units in the same site will have different T_{LRRT}.

If there are faults that require immediate service, then the potential operating cost savings for any other fault j of RTU_i that could be serviced at that time is

$$OCS_{asap,j,i} = EPDI_{j,i} \cdot OC_{normal,i} \cdot T_{RRT,j,i},$$

On the other hand, the potential operating cost savings for a fault repair scheduled for low season is

$$OCS_{low,j,i} = EPDI_{j,i} \cdot OC_{normal,i} \cdot (T_{RRT,j,i} - T_{SRRT})$$

where savings during the period from the point of diagnosis to low season are deducted. Especially for fouling and charge related faults, $OCS_{low,j,i}$ is zero ($T_{RRT,j,i} = T_{SRRT}$).

Similar to service cost estimation, economic fault evaluation should be based on a site rather than on equipment. The total operating cost savings for a site is the sum of the savings brought by all faults considered for repair based on economic criteria,

$$OCS_{asap,site} = \sum_i \sum_j OCS_{asap,j,i},$$

$$OCS_{low,site} = \sum_i \sum_j OCS_{low,j,i}.$$

5.3.10 Fault Decision—Overall Fault Decision

At any time when a set of diagnosed faults are obtained, fault decisions can be made according to the flow chart shown in Figure 31. It is assumed that if the capacity degradation is greater than a threshold (20% in this case), then comfort will be compromised in the future and the unit should be repaired. Similarly, the presence of refrigerant leakage leads to a fault repair decision. It can be seen that RRFs and a compressor leakage fault are treated in more detail because RRFs could absorb non-RRFs of the same unit and compressor leakage requires significant hardware replacement costs. Two global variables, $T_{service,free}$ and BC_{free}, are defined and initialized to be zero.

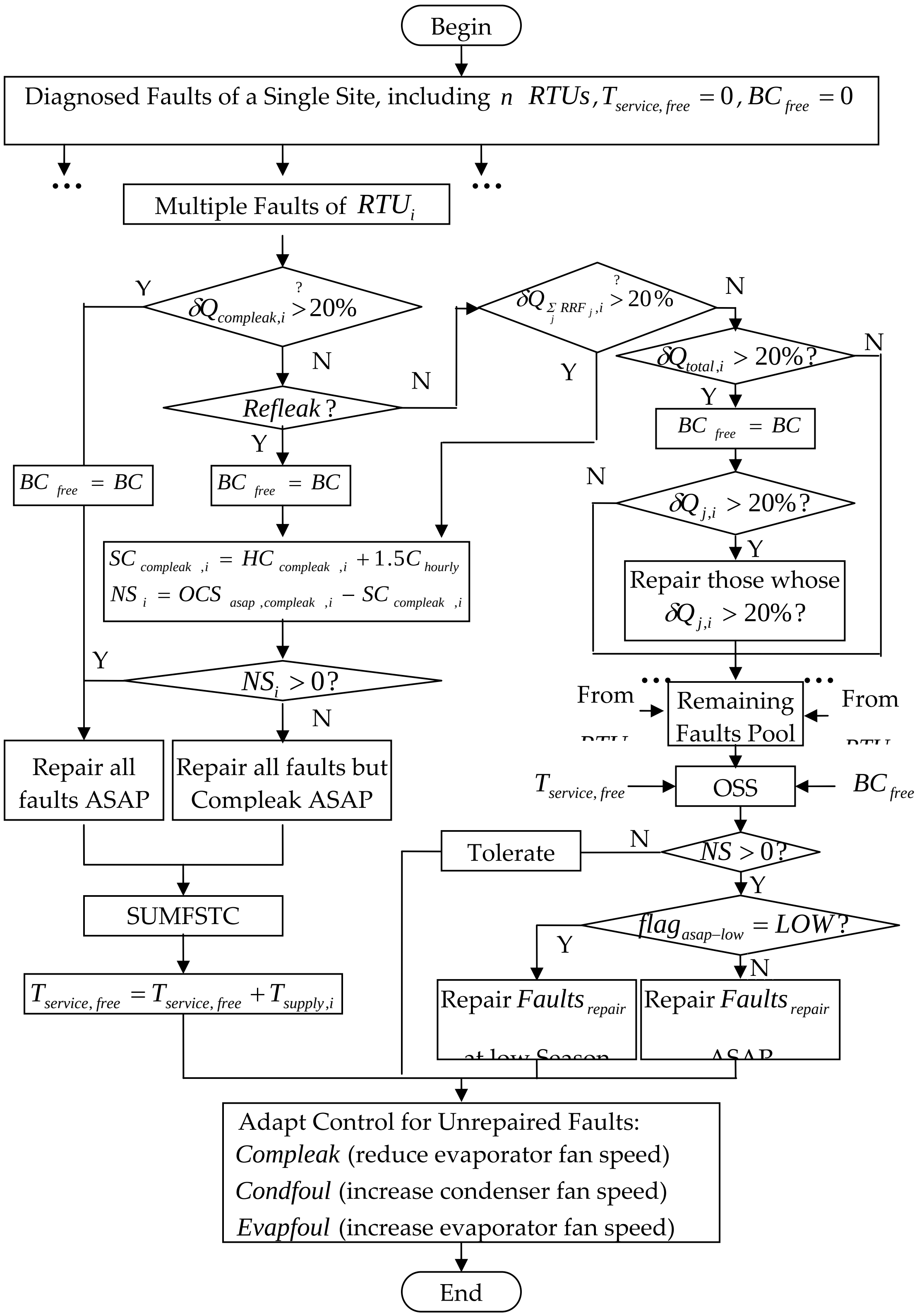
If the capacity degradation caused by compressor leakage is larger than the threshold ($\delta Q_{compleak,i} > 20\%$), all diagnosed faults should be repaired ASAP. Since a compressor leakage fault requires refrigerant recovery, it can absorb service times for the other CRFs and other RRFs on that unit and additional FRFs can be repaired using dead time associated with the recovery. BC_{free} is set as BC for other units, because the base visiting fee has been already paid.

If capacity degradation caused by compressor leakage is less than the threshold, but there is a refrigerant leakage fault, then service should be performed to repair the leakage and BC_{free} is set as BC for other units. A refrigerant leakage fault can absorb the labor costs for other faults on that unit, so all the other diagnosed faults except for compressor leakage fault should be repaired.

If capacity degradation caused by compressor leakage is not larger than the threshold and there is no refrigerant leakage fault, but the capacity degradation caused by diagnosed RRFs is larger than 20% ($\delta Q_{\sum_j RRF_j,i} > 20\%$), service should be performed to repair all the RRFs except for compressor leakage. In this case, the costs for repairing the other FRFs and CRFs on that unit can be absorbed into RRF costs. However, further evaluation of a compressor leakage fault is necessary to justify the compressor hardware costs. The total service costs for replacing a compressor can be calculated as

$$SC_{compleak,i} = HC_{compleak,i} + 1.5C_{hourly} \, .$$

Figure 31: The Fault Decision Flowchart



If the net savings ($NS_i = OCS_{asap,compleak,i} - SC_{compleak,i}$) is positive, a compressor leakage fault should be repaired. Otherwise, the compressor leakage fault can be tolerated.

There will be some free time available during the refrigerant recovery process on unit i that will be available for service on other units. The free time for unit i is $T_{supply,i}$ and an updated total free time is $T_{service,free} = T_{service,free} + T_{demand,i}$.

If capacity degradation caused by compressor leakage is less than the threshold and there is no refrigerant leakage and the capacity degradation caused by RRFs is less than the threshold ($\delta Q_{\sum_j RRF_j,i} < 20\%$), but the capacity degradation caused by all the faults is larger than the threshold ($\delta Q_{total,i} > 20\%$), comfort cannot be guaranteed and service should be performed ($BC_{free} = BC$). The individual faults causing more than 20% capacity degradation should be repaired and all the remaining faults should go to the remaining faults pool for economic evaluation. If capacity degradation caused by compressor leakage is not larger than 20% and there is no refrigerant leakage fault and capacity degradation caused by RRFs is less than the threshold ($\delta Q_{\sum_j RRF_j,i} < 20\%$) and capacity degradation caused by all the faults is less than the threshold, all the faults should go to the remaining faults pool for economic evaluation. In addition, those unrepaired faults of other units would go to the remaining faults pool.

All the faults in the remaining fault pool should be evaluated based on economic criteria: obtaining maximum economic savings. Economic savings is the difference in operating cost savings and service costs, both of which depend on the fault combination. So an optimal service searching (OSS) algorithm is developed to estimate the fault combination which would lead to maximum economic savings. The optimal service searching algorithm will be described in next section.

The OSS block outputs the maximum net savings (NS) and corresponding fault combination and schedule time. If net savings are less than 0 ($NS < 0$), all the remaining faults should be tolerated. Otherwise, service should be performed for those faults recommended for repair ($Faults_{repair}$) ASAP or in the coming low season. The schedule time flag, $flag_{asap-low}$, indicates when the service is performed.

Finally, those faults for which service is not performed ASAP require further decision to reduce the impact on comfort. If possible, an adapt control decision could be made: 1) for $Compleak$, the evaporator fan speed could be reduced to improve moisture removal (decrease SHR); 2) for $Condfoul$, the condenser fan speed could be increased; 3) for $Evapfoul$, evaporator fan speed could be increased.

5.3.11 Optimal Service Searching Algorithm

The number of possible fault combinations can be very large for a site. For example, for a five-unit site, if there are five possible faults for each unit, the total number of possible fault combinations would be 33,554,431 ($2^{5\times5}$ -1). It is prohibitive to evaluate this large number of combinations, so preprocessing should be performed to reduce the possible combinations.

Since the base visit fee accounts for 64% of the total service costs for FRFs and CRFs,, it is optimal to perform FRFs and CRFs together for the same unit. Therefore, for the same unit, FRFs and CRFs can be grouped together from the service point of view, and are termed FRFCRF. For RRFs excluding compressor leakage, termed RRFwoCLF, the recovery procedure accounts for 50% of the total service costs. Therefore, for a single unit, it is assumed to be optimal to combine repair of RRFs except for the compressor leakage fault. Repair of the compressor leakage fault requires expensive hardware costs, which accounts for 60% of this faults total service costs. Therefore, a compressor leakage fault should be separated from the RRFs and is termed compleak. So, there are only three types of faults considered for service based on economic criteria: FRFCRF, RRFwoCLF, and compleak. Within these three faults there are four more possibilities of fault combinations they are shown in the table below.

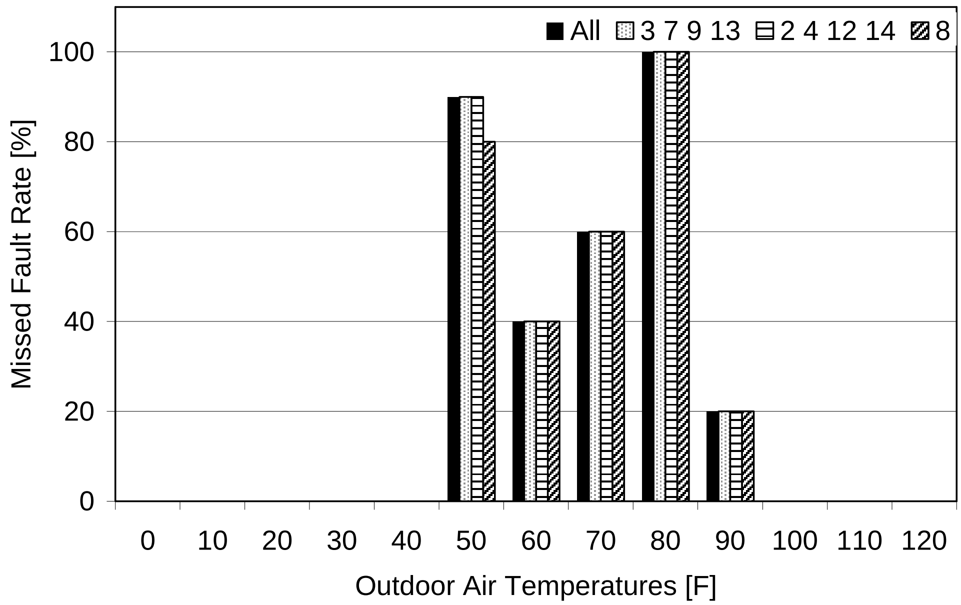
Table 11: Fault Service Priority Settings For A Given Site.

Fault Type
$FRFCRF_{RRFwoCLF\&compleak}$
$FRFCRF_{RRFwoCLF}$
$FRFCRF_{Compleak}$
$FRFCRF$
$RRFwoCLF_{FRFCRF\&compleak}$
$RRFwoCLF_{FRFCRF}$
$RRFwoCLF_{compleak}$
$RRFwoCLF$
$Compleak_{FRFCRF\&RRFwoCLF}$
$Compleak_{RRFwoCLF}$
$Compleak_{FRFCRF}$
$Compleak$

5.4 Project Outcomes

Results for the original diagnostic algorithm are divided according to the three fault groups that were implemented. More detailed results are presented for the damper fault group because the most significant algorithm improvements were identified for this group. All results presented here are for dry-bulb changeover control. An evaluation was also performed using differential control and the results were very similar. Results are presented as histograms of missed faults and false alarm rates according to bins of outdoor temperature. Each temperature bin covered a range of 10 F and included 10 different ambient conditions. The following table shows the results from the stuck damper fault.

Figure 32: Missed Fault Rate as A Function of OAT for the Stuck Open Damper Fault (OAF=1)



A stuck damper was simulated as being stuck in the full open condition.

Figure 32 shows results for this fault. The algorithm detected a stuck damper with a little more success than other damper faults but still had trouble when the OAT was slightly lower or higher than the RAT. The performance of the algorithm could be improved by adjusting the "low MAT" criterion. The "low MAT" fault setting is 40°F when it should be set closer to the MAT setpoint. The algorithm cannot detect the stuck damper when the OAT is slightly higher than the RAT due to an undetermined or invalid OAF calculation. When the OAF is not between zero and one, the algorithm will return an "invalid OAF." If the OAF is invalid, the fault cannot be detected.

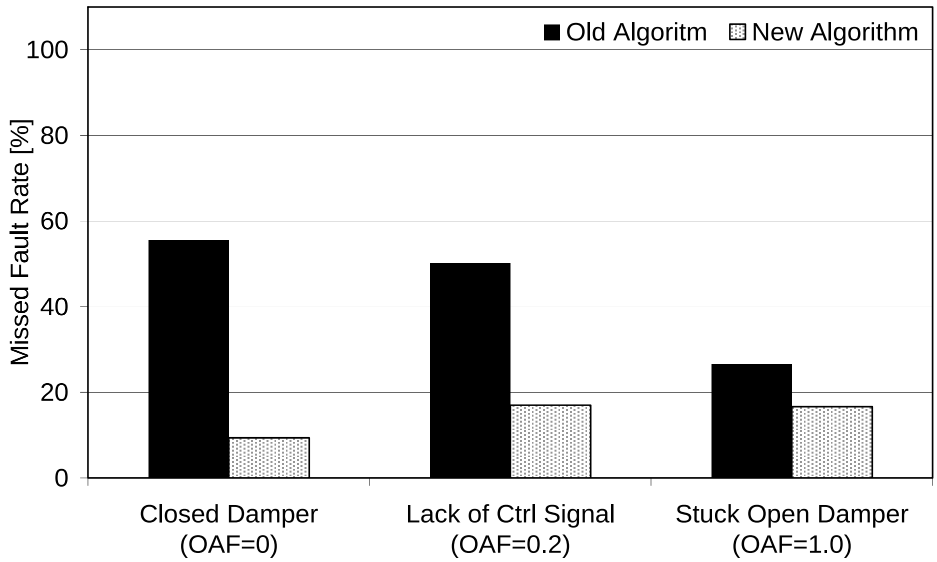
Missed fault rates were high for all of the faults implemented, especially for the damper faults. To improve the algorithm, some of the fault detection logic was rewritten and rearranged. For some, it was enough to just change the fault setpoint to improve detection. Through all of these changes, it was important not to increase the false alarm rate in the process.

Results for the improved algorithm are organized by fault type and directly compared with previous results to show the improved performance.

5.4.1 Damper Faults

The improvements to the algorithm were designed primarily to better detect damper faults and the improvement is dramatic.

Figure 33: Comparison of the Old and New Algorithms for Each Damper Fault



5.4.2 Controller Faults

The improved diagnostic criteria also had a significant impact on performance for the controller faults. Improving the "low mixed air temperature" and the "high OAF at high OAT" fault criteria allowed the algorithm to detect and correctly diagnose controller faults with a greater efficiency. Figure 34 and Figure 35 show comparisons between the old and new algorithms' missed fault rates for the MAT and minimum OAF setpoint, respectively.

Figure 34: Comparison Of Old And New Algorithm's Incorrect MAT Setpoint Missed Fault Rate For The Sensor Combination Using All Mixed Air Sensors.

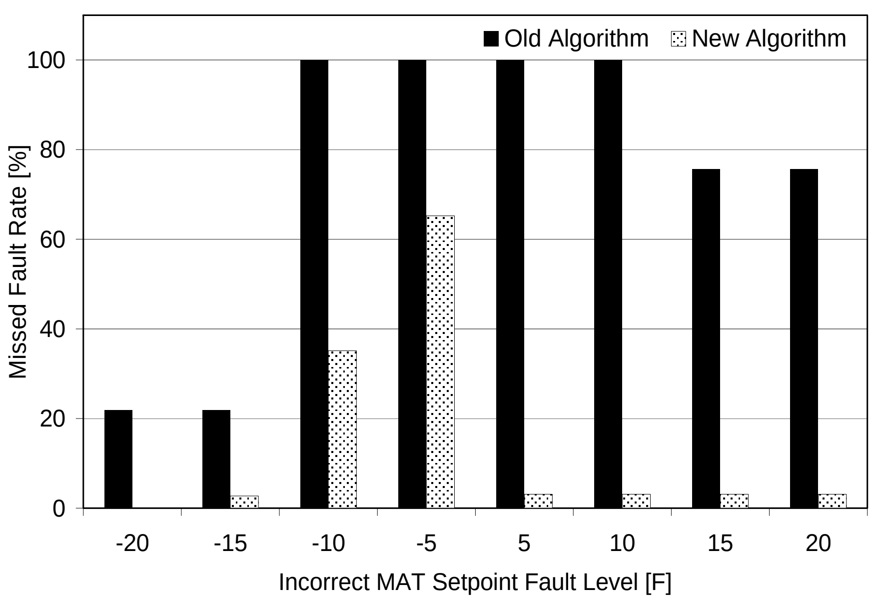
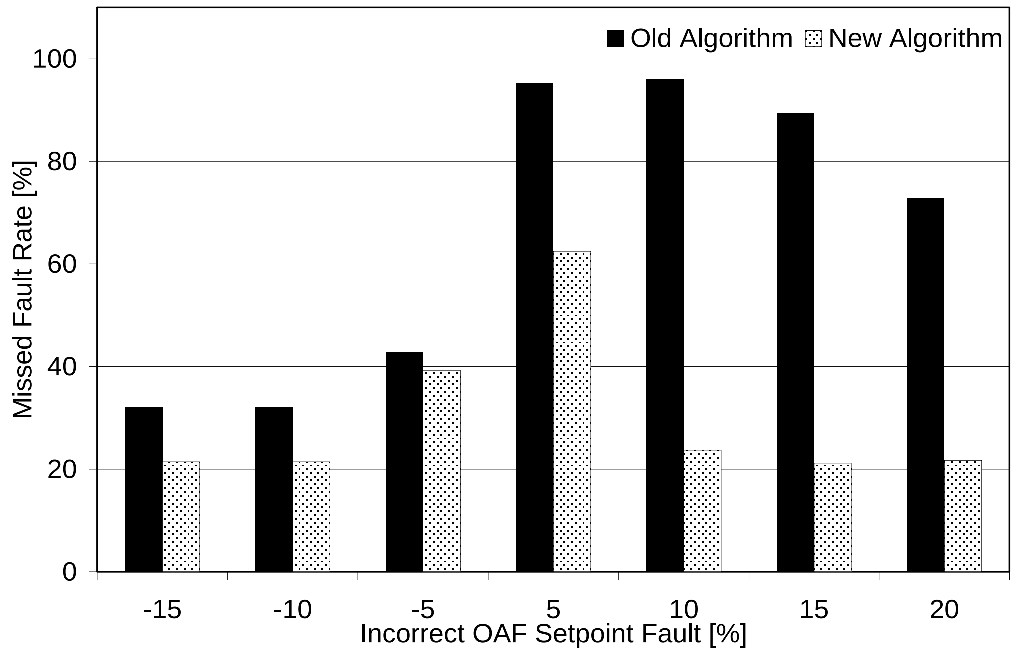


Figure 35: Comparison of Old and New Algorithm's Incorrect OAF Setpoint Missed Fault Rate for the Sensor Combination Using Mixed Air Sensors 3, 6, 10, and 13.



5.4.3 Sensor Faults

Improvements to the diagnostic algorithm had little effect on performance for detecting sensor faults. The current algorithm sets specific ranges of acceptable temperature measurements and adjusting these to better detect a fault like sensor bias is not practical. Figure 36 and

Figure 37 show comparisons between performance between the original and improved algorithms for sensor faults.

Figure 36: Comparison of Missed Fault Rates Averaged Over All Sensor Combinations and Fault Levels of the Sensor Bias Fault

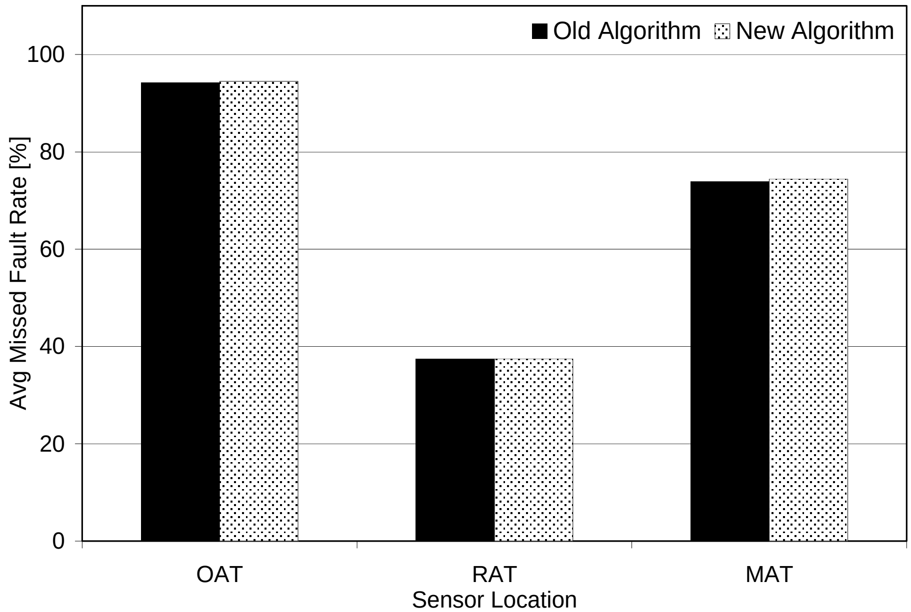


Figure 37: Comparison of Missed Fault Rates Averaged Over All Sensor Combinations of the Misplaced Sensor Fault

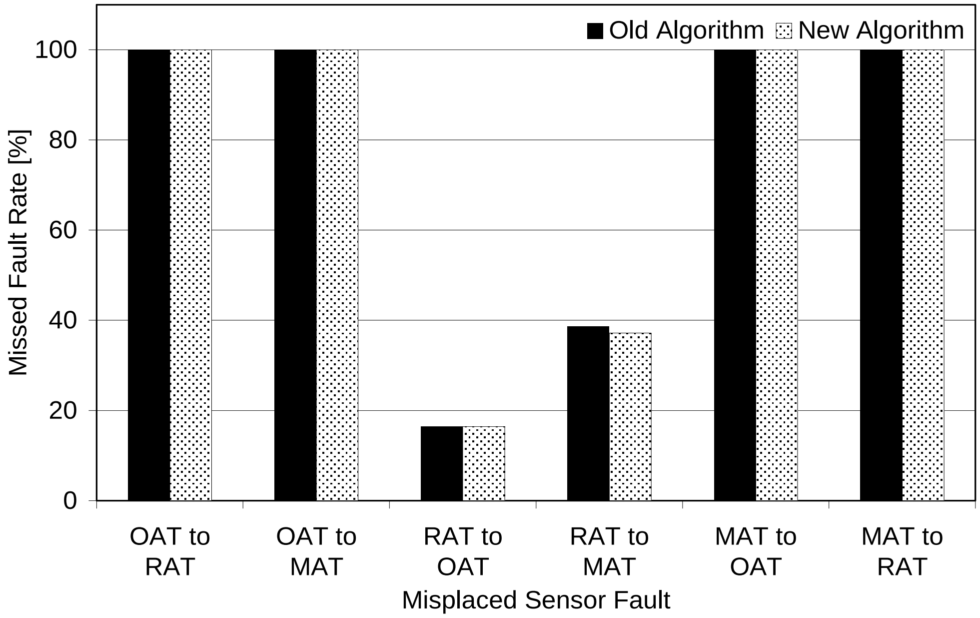
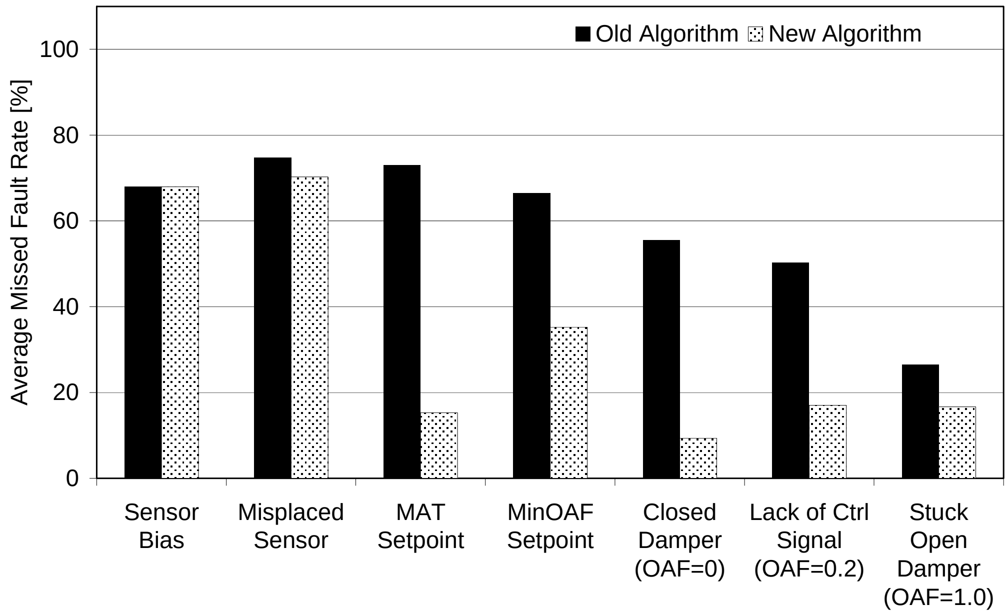


Figure 38 shows a summary comparison of missed fault rates for the two algorithms for dry-bulb changeover control. When the results were averaged over all sensor combinations, fault levels, and faults implemented the missed fault rate was reduced from 59.25% to 33.12%. If just the damper and controller faults are considered, the average missed fault rate improved from 54.37% to 18.73%. The algorithm was changed to specifically improve detection of these two types of faults. It would be difficult to improve the missed fault rate much because no matter what fault is implemented, there is always a range of OATs where the OAF cannot be accurately determined. This range makes up about 13% of all of the supplied operating conditions and sets a limit on how much the algorithm can be improved.

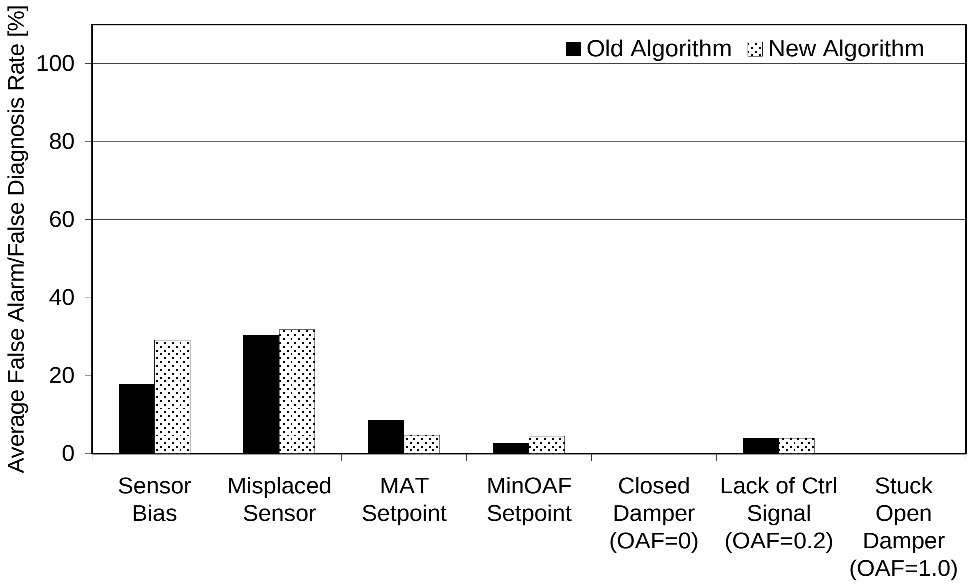
Figure 38: Comparison of the Missed Fault Rates for Every Fault Implemented Averaged Over All Fault Levels and Sensor Combinations Using Dry-Bulb Changeover Control



One of the concerns with changing the diagnostic algorithm was that even though missed fault rates would decrease, it could make the algorithm more susceptible to false alarms and false diagnoses.

Figure 39 shows false alarm rate comparisons for the two methods for all faults considered. The new algorithm did slightly increase the overall false alarm/false diagnosis rates using dry-bulb changeover control from 9.10% to 10.60%. Most of the increase occurred in the sensor faults. The damper and controller faults were not greatly affected. Some of the false alarms occurred when the OAT was between the outdoor air setpoint and the RAT (65 to 73°F). This range of temperatures could be considered poor conditions to run diagnostics on the system and the false alarms and missed faults in this area could be filtered out.

Figure 39: Comparison of the False Alarm/False Diagnosis Rates for Every Fault Implemented Averaged Over All Fault Levels and Sensor Combinations Using Dry-Bulb Changeover Control



Differential dry-bulb control yielded similar missed fault and false alarm rate results to dry-bulb changeover control. The overall average missed fault rate improved from 63.39% to 33.45%. Considering just the damper and controller faults, the missed fault rate went from 60.01% for the original algorithm to 18.04% with the improved algorithm. Using differential control, the false alarm/false diagnosis rates improved slightly between algorithms from 10.64% to 10.39%. It is more important to note that the algorithm changes did not have a significant effect on the false alarm rate.

5.5 Two Case Studies for Training

The 10-bin MAT correlation increases the accuracy of the single-point MAT. However, this correlation was developed with a full set of temperature data with OATs that ranged from 20-115°F. If this system were implemented in the field, it could take at least six months for the building system to see that large of a range of OATs and collect the data. The case studies presented here demonstrate the effectiveness of the MAT_{error} correlation without a full set of training data. The first case study represents a system that has only collected data in the winter, and the second represents a system that has only collected data in the summer.

5.5.1 Winter Data

For this case, data points with OATs ranging from 20-40°F were used to develop the correlation for predicting the MAT_{error}. Using just this data, there were several data points per bin so each normalized damper control signal was well represented. This correlation was then applied to all of the data and the RMS errors were calculated for the corrected MAT and the calculated OAF. Figure 40 compares the MAT corrected with this correlation to the baseline MAT and

Figure 41 compares the OAF calculated with the MAT corrected by this correlation to the OAF calculated with the baseline MAT. The RMS errors for MAT and OAF are 1.1415°F and 0.0598, respectively. Both of these values show that this correlation is a significant improvement over the uncorrected single-point measurement but not as effective at correcting the MAT as the correlation developed using all of the economizer data.

Figure 40: Corrected Single-Point, 10-Bin MAT Correlation Trained Using Winter Data Compared to MAT Baseline

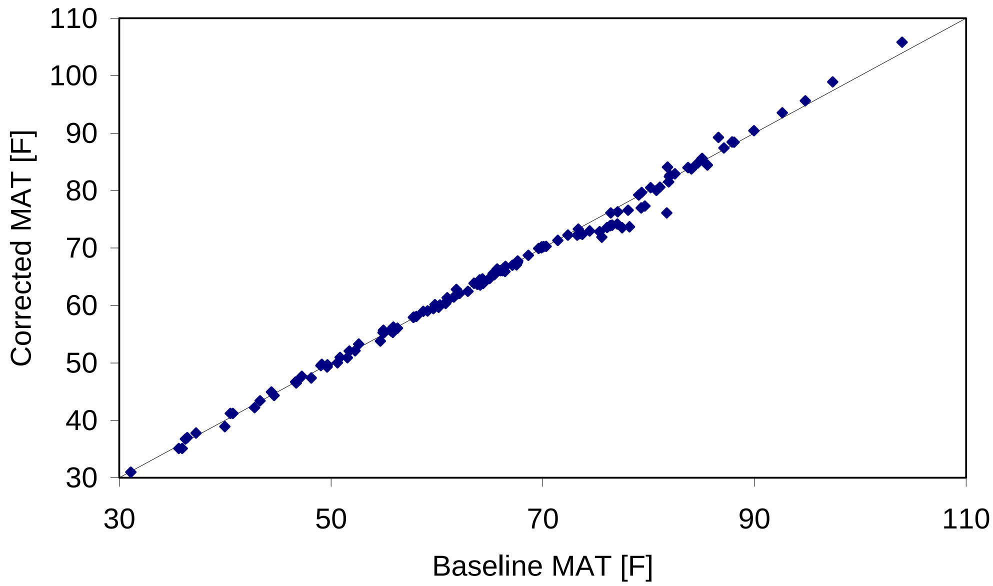
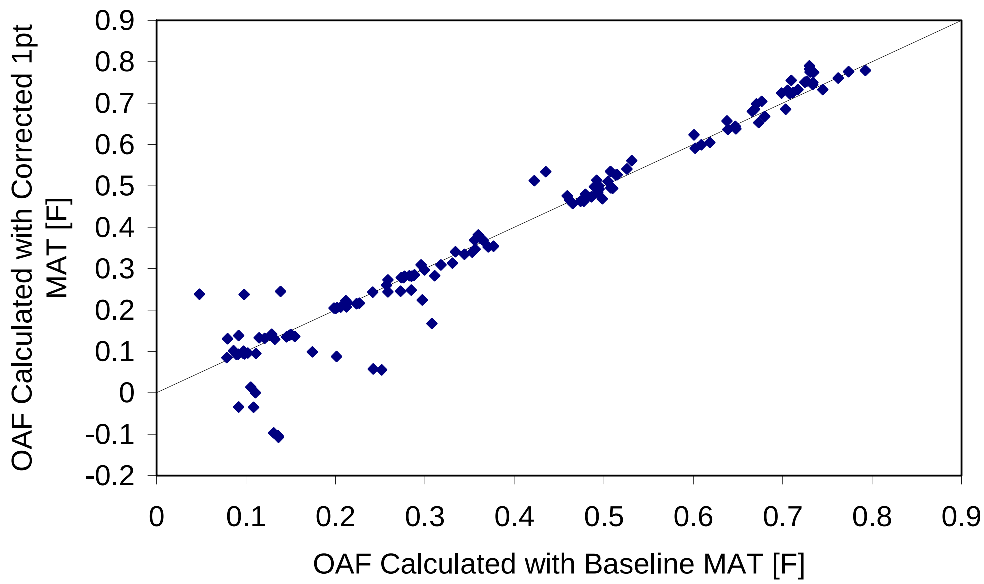


Figure 41: OAF Calculated with Single-Point, 10-Bin MAT Correlation Trained With Winter Data Compared to the OAF Calculated with the Baseline MAT



5.5.2 Summer Data

The correlation for this case was developed using OAT data in the range of 85-105°F. This data set did not cover the entire normalized damper control signal range as well as the winter case did. Several of the bins only had two data points. As a result, the correlation developed using this data yielded a very poor correction when applied to data outside of the range used for training. Figure 42 and

Figure 43 show results for MAT and OAF over the entire range of economizer data for correlations trained with summer data. The RMS errors calculated for the MATs and the OAFs are 8.2056°F and 0.2311 respectively, which are significantly worse than the results for the uncorrected single-point MAT. It is critical to have training data over a wide range of ambient temperatures and damper positions.

Figure 42: Corrected Single-Point, 10-bin MAT Correlation Trained Using Summer Data Compared to the MAT Baseline

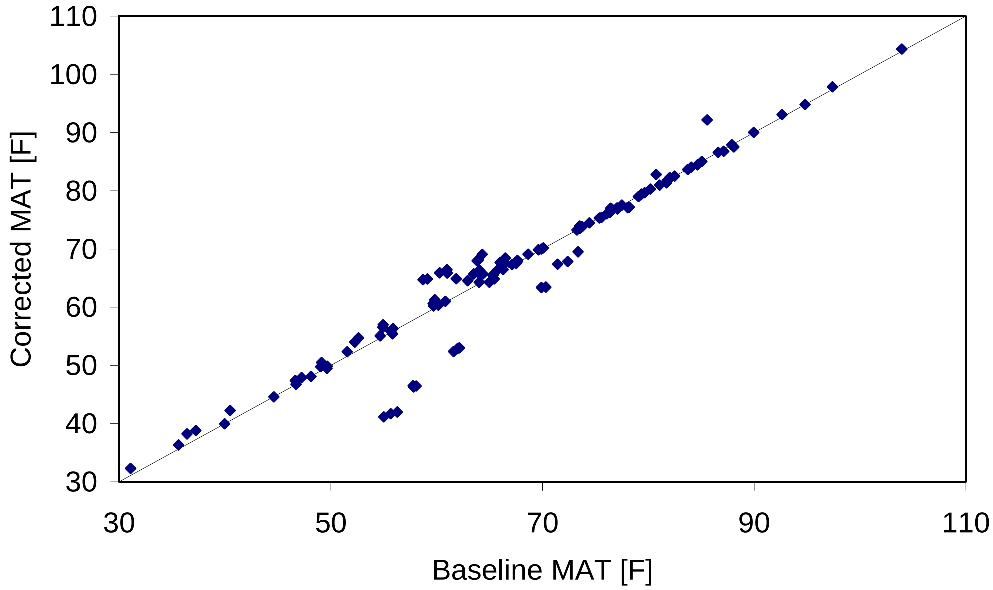
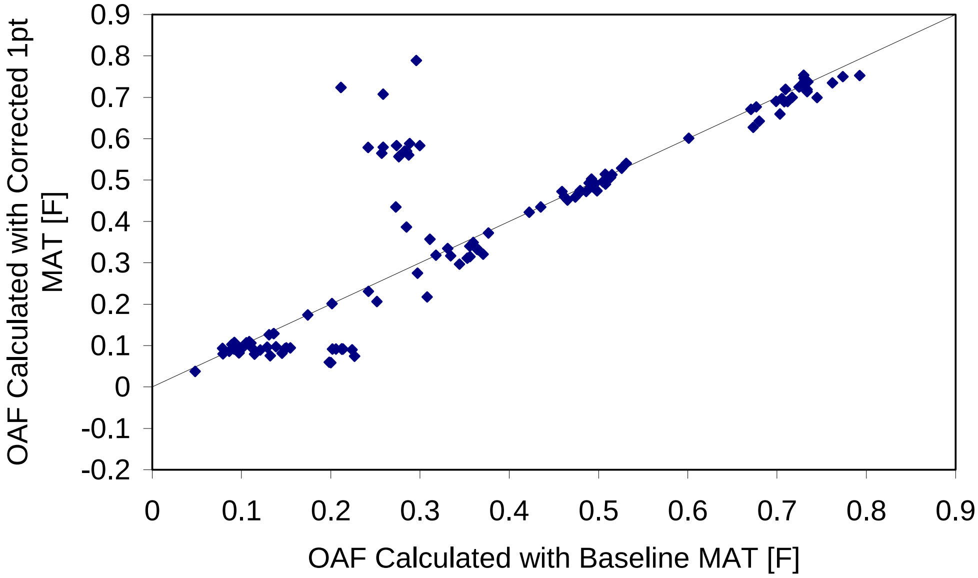


Figure 43: OAF Calculated with Single-Point, 10-Bin MAT Correlation Trained with Summer Data Compared to the OAF Calculated with the Baseline MAT



5.6 Fault Evaluation and Decision Making

Multiple-simultaneous-fault data collected from the Purdue field emulation site are used to demonstrate the proposed methods. The installed system is a 5-ton rooftop unit with an EER of 11. Multiple-simultaneous-fault combinations of six faults were considered. Only one fault level was implemented for each combination, because there are infinite combinations if fault level is considered. Except for compressor leakage, all the other faults were implemented at the levels between the first diagnosed and next levels. Compressor leakage was implemented at different and relatively high fault levels to test the fault evaluation algorithm. Fault levels of condenser fouling and liquid-line restriction and refrigerant overcharge were fixed, while two fault levels of refrigerant leakage and evaporator fouling were simulated and compressor leakage fault levels ranged from 20% to 35%. Since refrigerant charge faults are mutually exclusive, the total number of combinations is the sum of those at low charge,

$$C_r^1 + C_4^2 + C_4^3 + C_4^4 = 15,$$

normal charge,

$$C_4^2 + C_4^3 + C_4^4 = 11,$$

and over charge,

$$C_r^1 + C_4^2 + C_4^3 + C_4^4 = 15.$$

All forty-one combinations with individual fault levels implemented are listed in Table 18. The following assumptions are made:

Base visiting fee, BC, is \$115, and hourly rate, C_{hourly}, is \$65;

Normal equipment life, $T_{equipmentlife}$, is 10 years and 12,000 hours of runtime;

The average equipment costs, including capital costs and initial installation, are \$875 per ton;

The average maintenance and service costs are \$40 / (year-ton);

$\bar{C}_{electricity} = \$0.1$;

Yearly runtime is 1500 hours,

Discount rate for low season (α_{low}) is 0.5.

Table 12: Individual Fault Levels Implemented In Multiple-Simultaneous-Fault

Test No.	compnv	condfoul	evapfoul	llrestr	refleak	refover
1	27%	0	0	0	14%	0
2	27%	11%	0	0	14%	0
3	25%	11%	12%	0	11%	0
4	25%	11%	12%	12%	11%	0
5	0	11%	12%	12%	11%	0
6	0	0	12%	12%	11%	0
7	0	0	0	12%	14%	0
8	29%	0	0	12%	14%	0
9	25%	0	12%	12%	11%	0
10	25%	0	12%	0	11%	0
11	0	0	12%	0	11%	0
12	0	11%	12%	0	11%	0
13	0	11%	0	0	14%	0
14	0	11%	0	12%	14%	0
15	29%	11%	0	12%	14%	0
16	32%	11%	0	0	0	0
17	21%	11%	12%	0	0	0
18	21%	11%	12%	12%	0	0

Test No.	compnv	condfoul	evapfoul	llrestr	refleak	refover
19	0	11%	12%	12%	0	0
20	0	0	12%	12%	0	0
21	19%	0	12%	12%	0	0
22	32%	0	0	12%	0	0
23	0	11%	0	12%	0	0
24	32%	11%	0	12%	0	0
25	0	11%	12%	0	0	0
26	19%	0	12%	0	0	0
27	33%	0	0	0	0	21%
28	32%	11%	0	0	0	21%
29	35%	11%	16%	0	0	21%
30	35%	11%	16%	12%	0	21%
31	0	11%	16%	12%	0	21%
32	0	0	16%	12%	0	21%
33	0	0	0	12%	0	21%
34	32%	0	0	12%	0	21%
35	35%	0	16%	12%	0	21%
36	35%	0	16%	0	0	21%
37	0	0	16%	0	0	21%
38	0	11%	16%	0	0	21%
39	0	11%	0	0	0	21%
40	0	11%	0	12%	0	21%
41	32%	11%	0	12%	0	21%

Table 13: Fault Evaluation for multiple-simultaneous faults

Test No.	$r_{\Delta cap}$	$r_{\Delta EER}$	$r_{\Delta SHR}$	$EPDI$	Decision	SC ($)	$T_{payback}$ (year)
1	0.28	0.19	-0.06	0.27	ASAP	892.5	2.1
2	0.31	0.25	-0.09	0.29	ASAP	892.5	1.9
3	0.25	0.20	-0.06	0.25	ASAP	892.5	2.3
4	0.27	0.22	-0.04	0.30	ASAP	892.5	1.9
5	0.09	0.12	0.14	0.31	ASAP	472.5	1.0
6	0.05	0.04	0.12	0.20	LS	164.1	0.5
7	0.05	0.00	0.10	0.15	LS	119.1	0.5
8	0.30	0.21	-0.06	0.31	ASAP	892.5	1.8
9	0.26	0.17	-0.02	0.28	ASAP	892.5	1.9
10	0.25	0.17	0.00	0.30	ASAP/Compleak (LS)	213/ 580	1.2/4.5
11	0.04	0.01	0.10	0.14	Tolerate		
12	0.05	0.09	0.08	0.18	Tolerate		
13	0.06	0.07	0.04	0.12	Tolerate		
14	0.06	0.06	0.10	0.19	LS	237	0.8
15	0.29	0.23	-0.07	0.30	ASAP	892.5	1.9
16	0.34	0.28	-0.18	0.26	ASAP	860	2.0
17	0.25	0.21	-0.02	0.29	ASAP	860	1.8
18	0.21	0.17	-0.03	0.22	ASAP	893	2.5
19	0.06	0.10	0.09	0.20	LS	220	0.7
20	0.01	0.00	0.08	0.09	LS	220	1.4
21	0.21	0.14	-0.02	0.21	ASAP	860	2.6
22	0.33	0.24	-0.15	0.25	ASAP	860	2.1
23	-0.03	0.04	0.02	0.02	LS	220	5.7
24	0.28	0.25	-0.15	0.21	ASAP	860	2.5
25	0.06	0.10	0.06	0.16	ASAP	180	0.7
26	0.20	0.13	-0.05	0.16	Tolerate		

Test No.	$r_{\Delta cap}$	$r_{\Delta EER}$	$r_{\Delta SHR}$	$EPDI$	Decision	SC ($)	$T_{payback}$ (year)
27	0.30	0.23	-0.16	0.20	ASAP	860	2.7
28	0.28	0.24	-0.17	0.18	ASAP	860	3.0
29	0.39	0.35	-0.09	0.50	ASAP	860	1.1
30	0.36	0.33	-0.09	0.44	ASAP	860	1.2
31	0.08	0.15	0.08	0.24	LS	220	0.6
32	0.07	0.08	0.09	0.20	LS	220	0.7
33	-0.03	-0.01	0.00	-0.02	Tolerate		
34	0.32	0.25	-0.13	0.27	ASAP	860	2.0
35	0.38	0.31	-0.06	0.48	ASAP	860	1.1
36	0.38	0.31	-0.07	0.49	ASAP	860	1.1
37	0.07	0.08	0.08	0.18	Tolerate		
38	0.08	0.15	0.07	0.23	LS	123	0.3
39	0.03	0.10	-0.01	0.06	Tolerate		
40	0.03	0.11	0.01	0.09	LS	220	1.5
41	0.34	0.31	-0.16	0.31	ASAP	860	1.7

Table 12 tabulates all the fault evaluation and decision results in terms of performance degradation (including capacity degradation $r_{\Delta cap}$, EER degradation $r_{\Delta EER}$, SHR degradation $r_{\Delta SHR}$ and EPDI), fault decision, service costs (SC) and payback period.

Since this field emulation site only has one RTU, there is no potential service savings related to multiple unit services and the service costs would be relatively high.

As shown in Table 13: Fault Evaluation for multiple-simultaneous faults, twenty-three of the forty-one multiple-fault tests require service as soon as possible (ASAP), ten cases were scheduled for low season (LS), seven cases can be tolerated until more faults have developed such as fouling faults, and there is one case (Number 10) that requires service ASAP but with compressor leakage fault scheduled for low season (LS). As an example, the service costs for those faults requiring ASAP service in Test No. 10 were $213 and the payback period was 1.2 years and the service costs for compressor leakage were $580 and its payback period ($T_{payback}$) was 4.5 years.

5.7 Conclusions and Recommendations

Refrigerant pressures are important for monitoring, control, optimization and diagnostics of vapor compression cycle equipment. However, the use of permanently mounted pressure sensors is expensive due to both sensor hardware and installation and can lead to refrigerant leakage when applied for retrofits. This section described methods for inferring pressures from low-cost surface-mounted temperature measurements. The key issues that were addressed in the development included identification of appropriate locations for measuring saturation refrigerant temperatures and correcting for pressure drops to allow pressure estimates at other locations of interest. Experimental evaluation demonstrated that the virtual pressures have comparable accuracy to direct pressure measurements and work well when used for fault diagnoses.

5.7.1 Recommendations

5.7.1.1 Sensor Faults

Two methods are suggested for improving the detection of sensor faults. The first method is designed to improve detection of a misplaced temperature sensor. When a temperature sensor has been physically placed in the wrong location in the system, it is likely that two temperature sensors in the system will be read almost the same value regardless of the operating conditions. For example, if the outdoor air sensor was removed during routine maintenance then replaced in the return air position, both the OAT and RAT would read about the same temperature in the return air duct. This by itself cannot be detected with the current diagnostic algorithm, but a new criterion could look for two of the economizer system temperatures to stay within 2°F for a 24 hour period. Over the course of a typical day, the OAT and MAT should have more than a 2°F temperature change. Therefore, the misplaced sensor fault could be detected.

To detect bias in the sensors would require a different approach than just adding a new fault criterion. Adding a sensor calibration procedure into the FDD algorithm would allow detection of sensor problems. To calibrate the sensors, the algorithm would require an internet connection to determine local weather conditions and active damper control. First, the local OAT would be obtained from an internet source. Then, the damper would be placed in the fully open condition, making the OAF equal to 1.0 and the OAT equal to the MAT. The weather station can then be compared with the measured system OAT and MAT. If they are all equal within some tolerance for error, the damper would then be closed. With an OAF equal to 0.0 and the MAT theoretically equal to the RAT and the MAT's accuracy verified, the measured system MAT can be compared to the RAT to check for a fault. If any of the sensors fail this check, all of the sensors should be examined for faults. This sensor calibration procedure could be performed at regular intervals as part of a maintenance routine to insure there is no sensor bias in the economizer system.

5.7.1.2 Damper Faults

The current economizer algorithm uses simple rules based on the OAT, RAT, MAT, and calculated OAF to detect faults with the damper. It is also possible to determine an "expected" value for OAF (OAFspt) that is based on the MAT setpoint and measurements of OAT and MAT. The current OAF could be compared with OAFspt to identify a fault. For example, if the OAF should be 0.7 but it is calculated to be 0.21, this would clearly indicate no economizer cooling at a low OAT fault. This technique could be integrated into the current algorithm and provide a simple warning message stating that the damper is out of position. Then, the current fault logic could be used to perform the diagnosis.

Using experimental data obtained from a laboratory setup, an economizer model was developed so that faults could be simulated and diagnostic algorithms could be evaluated. The economizer model determines the correct outdoor air fraction using the programmed controller logic and measurements of OAT and RAT. Mixed air temperature sensor readings are predicted by the model based on the OAT, RAT, OAF, and a specified mixed air sensor combination. The economizer experiments, in addition to the literature, provided useful insights in creating a list of faults to implement within the economizer model. Eight different faults and five different combinations of mixed air temperature sensors were simulated and used to evaluate diagnostic performance. This was done for both dry-bulb changeover and differential dry-bulb control methods. An existing algorithm was evaluated and then improved. The improved FDD algorithm resulted in a 26% decrease in missed faults when using dry-bulb changeover control, and a 30% decrease when using differential dry-bulb control. False alarm and false diagnosis rates were not significantly changed as a result of the algorithm improvements.

5.7.1.3 Smart Mixed Air Temperature Sensor

An accurate mixed air temperature (MAT) measurement is important for diagnostic systems used for economizers and air conditioners. However in many installations for small commercial equipment, the configuration of the mixing chamber and the dampers make it difficult to obtain an accurate measurement of the MAT. This section proposed a method for correcting a single-point MAT measurement. The correction correlates the error in MAT to damper position and difference between outdoor and return air temperatures. The baseline MAT is taken as the supply air temperature from the unit when the compressor is off corrected for the fan temperature rise. Both the fan temperature rise and error in MAT are learned during a self-calibration mode under conditions where the compressor is off and then used for any operating condition.

It was shown that this correction method can provide a significant improvement in the accuracy of MAT when employing single-point, two-point, and even four-point temperature measurements. Furthermore, estimates of outdoor air fraction are significantly improved. However, it is necessary to train the correction correlation over a wide range of ambient conditions and damper positions.

Two case studies were considered for training of the correction correlation with limited data. Both of these case studies reveal two important details about this MAT correction method if it were to be implemented in real-world applications. The first is that for this method to work there needs to be several data points collected for a wide range of ambient conditions over the entire range of damper positions. A correlation based on the use of limited summer data actually produced a worse result than if the single-point MAT was left uncorrected because not all damper positions had a range of ambient temperature data. However, a correlation developed from winter data over a wide range of damper positions worked well over the entire range of operation.

The second important detail is that this method needs to have a consistent schedule of collecting data in its self-calibration mode. By doing this over time, the MAT correction correlation can be updated and improved. A system newly installed in the field will have a limited data set to create the correlations. Fortunately, this data set should be adequate to correct the MAT for the current season and only limited extrapolation of the correlation would be necessary. As the seasons change, more data would be collected, and the correlation would be improved. The summer case study showed that a limited data set extrapolated to other OATs will not perform well.

5.7.2 Fault Evaluation and Decision Making

Methods for estimating operation cost savings and fault service cost associated with repairing diagnosed faults were proposed. Based on the operation cost savings and service cost estimation methods, fault evaluation and decision were performed, which are essentially an optimization problem for minimizing the total costs of operation and service. In order to reduce the computation complexity, an optimal service searching algorithm was proposed. Finally, validation of the proposed methods was described. Multiple-simultaneous-fault data collected from the Purdue field emulation site were used to demonstrate the proposed methods. Twenty-three of the forty-one multiple-fault tests required service as soon as possible (ASAP), ten cases were scheduled for low season (LS), seven cases could be tolerated until more faults developed such as fouling faults, and there was one case (Number 10) that required service ASAP but with compressor leakage fault scheduled for low season (LS). As an example, the service costs for those faults requiring ASAP service in Test No. 10 were \$213 and the payback period was 1.2 years and the service costs for compressor leakage were \$580 and its payback period ($T_{payback}$) was 4.5 years.

CHAPTER 6: Project 6: SpeciFlow™ Technology

6.1 Introduction

Federspiel Controls has developed a new airflow measurement and control technology called SpeciFlow™. The SpeciFlow™ SF-1000 performs better and is less expensive than the leading product of its kind on the market (Ruskin's IAQ50). SpeciFlow™ airflow control technology works by integrating pressure pickups, a temperature sensor, and a position sensor with stock control dampers. An empirically determined calibration curve embedded in a programmable controller is used to relate pressure, temperature, and position to flow rate. The controller adjusts the position of the damper so that the computed flow rate tracks the desired flow rate. Although SpeciFlow™ technology could be applied to any airflow measurement and control application that requires a control damper, the target application is direct measurement and control of outdoor airflow rate.

There is a need for further development in three areas: generic calibration curve, sensitivity to non-uniform flow, and new I/O features.

There is a need to develop a generic calibration curve that compensates for the effects of geometry and damper design so that it is not necessary to calibrate every unit. The SF-1000 is insensitive to non-uniform flow when the control damper on which it is installed is less than 70% open. When the damper is 70-100% open, the SF-1000 is sensitive to non-uniform flow, and it is necessary to use expensive flow straighteners to reduce the sensitivity to non-uniform flow in that operating range.

There is a need to develop a low-cost method that will make it insensitive to non-uniform flow.

The low-cost method of reducing sensitivity to non-uniform flow will require additional I/O.

6.2 Project Objectives

The objectives for this Project were to:

develop a generic calibration curve so that 5% accuracy can be achieved without individual calibration

develop a method that makes SpeciFlow™ technology insensitive to non-uniform flow over all operating conditions

add additional I/O to the SpeciFlow™ hardware

6.3 Project Approach

Key tasks and the approach by the project team are summarized as follows.

6.3.1 Generic Calibration Curve (Task 6.2)

The technical approach for Task 6.2 involved analysis of calibration data from production dampers calibrated as part of the initial order delivery process. We analyzed three pairs of nominally identical dampers with the following sizes: 48 inches wide by 38 inches high, 24 inches wide by 54 inches high, 24 inches wide by 60 inches high. The dampers are referred to as A, B, C, D, E, and F. Dampers A and B are a matched pair, as are (C,D) and (E,F). All six dampers have opposed-blade operation.

We compared the calibration curves of each matched pair of dampers. We computed an "average" calibration curve for each pair from the four sets of calibration data for that pair, and then computed the relative accuracy using the average calibration curve for all face velocities between 300 feet per minute and 2000 feet per minute. The relative accuracy is the difference between the measured airflow and the airflow predicted using the average calibration curve as a percent of the measured flow.

6.3.2 Correction for Non-Uniform Flow (Task 6.3)

The original approach was to investigate two methods for detecting and correcting for non-uniform flow when a control damper is more than 70% open. This approach involved conducting tests on control dampers with additional instrumentation designed to provide the necessary information to detect and correct for non-uniform flow. We tested two methods of correcting for non-uniform flow. The first involved using two pairs of pressure sensors instead of a single pressure sensor. One pair should correct for vertical non-uniformity, and the other should correct for horizontal non-uniformity. This approach is similar to using an array of pilot tubes except that the pressure sensors measure differential pressure across the damper blades at four locations.

The second method was attempted to correct for non-uniform flow by measuring the non-uniformity of the static pressure field at the leading edge of the damper with two pressure sensors. One measured the vertical gradient, the other will measure the horizontal gradient. The position-dependent flow coefficient of the damper was modified proportionally by the measured magnitude of the gradient in the vertical and horizontal direction. This method reduces the need for one pressure sensor; it only requires three.

6.3.3 Engineering for Enhanced Market Adoption (Task 6.4)

Based on input from Greenheck and feedback from their sales representatives, we developed the following input-output specification for the SpeciFlow™ controller:

6.3.3.1 General

Must be able to interface with a modulating electric actuator

6.3.3.2 Inputs

Must accept a 0-10 VDC analog input for position

Must accept a 0-5 VDC analog input from an external pressure sensor

Must accept a resistance input from a thermistor

Must accept a binary input that will switch the controller from flow control mode to position control mode

6.3.3.3 Outputs

Must provide a 0-10 VDC analog output for position

Must provide a 0-10 VDC analog output for airflow rate

Must provide a 0-10 VDC analog output for temperature

6.3.3.4 Communications

Must be able to communicate with a building control system using LONTALK® communications protocol on an Echelon® LONWORKS® network.

6.3.3.5 Power

Must operate on 24 VAC provided by a Class 2 transformer.

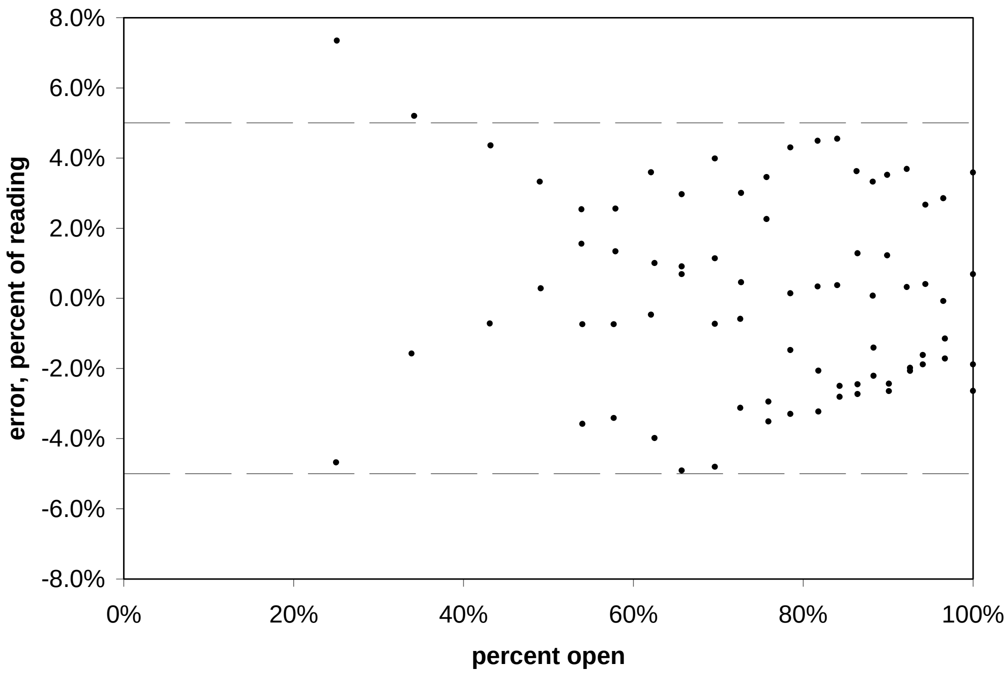
6.4 Project Outcomes

A summary of the project outcomes follows.

Most of the time manufacturer variability is small enough to use a generic calibration curve.

This section only includes one example, Figure 44: Relative Error for the Average Calibration Curve of Dampers (A, B), that show the relative accuracy of pairs (A,B), (C,D), and (E,F), respectively. The specification is 5% of reading or less for face velocities between 300 feet per minute and 2000 feet per minute. Data points with face velocities less than 300 feet per minute were omitted, which is why there are no data points at positions less than 20% open. The dashed lines show the boundaries of the specification.

Figure 44: Relative Error for the Average Calibration Curve of Dampers (A, B)



Pairs (A, B) and (E, F) compare favorably. Only two of the 76 points for (A, B) are outside the specification of 5% of reading, while none of the points for (E, F) are outside the specified accuracy range.

The agreement between C and D is not as good, with 19% of the points outside the specified range. Since the size of C and D is similar to the size of E and F, we compared the calibration curves of C to E and F, and we also compared the calibration curves of D to E and F. Damper C has a different calibration curve than dampers E and F, while damper D has the same calibration curve as dampers E and F. These results suggest that there must have been some aspect of the way that damper C was manufactured that altered its calibration curve from the standard curve for that damper size. The fact that the Damper D calibration curve is the same as the Damper E and Damper F calibration curves demonstrates that small differences in damper size have a small difference on the calibration curve. We expected that this would be true; these results confirm this hypothesis.

The results also show that even when dampers have the same calibration curve (e.g., A and B), the small differences from damper to damper may cause the accuracy to be outside the specification when the damper is marginally open (e.g., 25% open). This is because the face velocities under these conditions are low even at the highest pressure that the pressure sensor can read. This implies that each damper must be calibrated at this position or at least checked for accuracy at this position prior to shipping.

Correction for non-uniform flow is possible with sensors but not practical.

We found that neither of the approaches for addressing the original objectives of this task was successful at eliminating sensitivity to non-uniform flow. Figure 7 shows an example of the first method, where four pressure sensors are used, one for each quadrant of the damper. In this case the damper had airfoil blades with opposed operation. The damper was calibrated without an upstream flow disturbance (louver), then tested with a louver in place. In this case the louver was oriented with the blades horizontal and deflecting air upward. The agreement between the wind tunnel flow and the SpeciFlow™ damper flow clearly becomes poor when the damper is more than 70% open (square symbols). The two diagonal lines on Figure 45: Method 1 Results for One Case correspond to the 5% accuracy boundary. The points taken when the damper is less than 70% open (round symbols) are highly co-linear, but they lie above the upper limit. This problem could be fixed by using unequally weighted averages of the four readings, but a procedure would be required to determine the weights. The averaging doesn't retain the colinearity when the damper is more than 70% open because the louver placed upstream of the damper induces a very large non-uniform flow disturbance. Under some conditions, the flow reverses at the bottom of the damper.

Figure 45: Method 1 Results for One Case

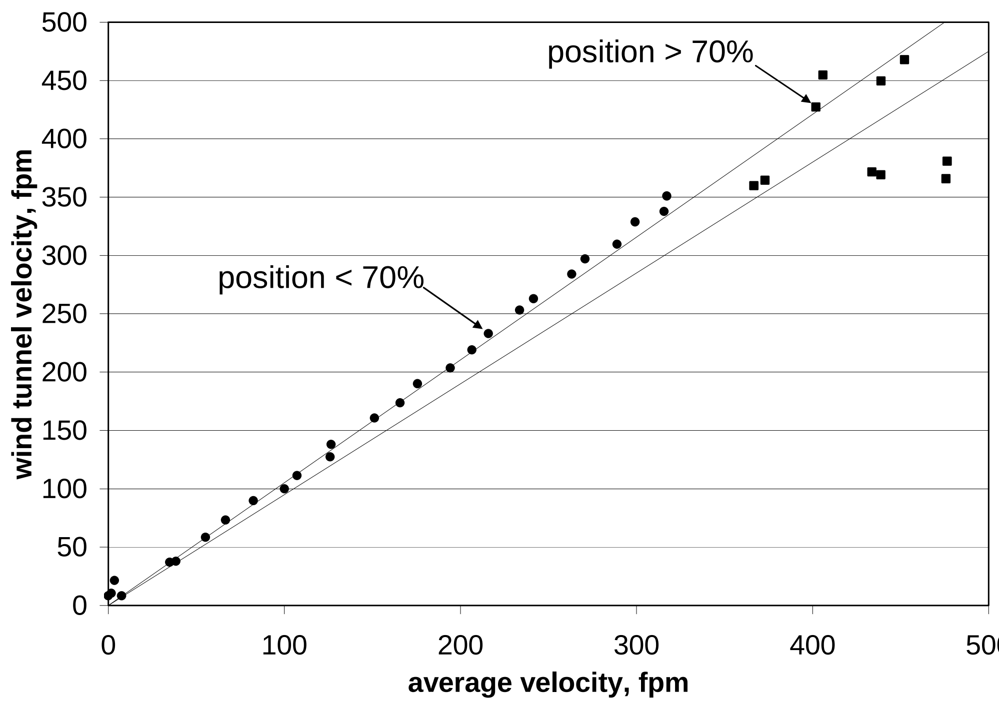


Figure 45: Method 1 Results for One Case shows an example of the results from applying the second method, where three pressure sensors are used. One pressure sensor is used to measure the pressure difference between the high pressure and low pressure pickups on the blades,

another sensor is used to measure the vertical pressure gradient at the leading edge of the damper, and a third sensor is used to measure the horizontal pressure gradient at the leading edge of the damper.

shows the agreement between the SpeciFlow™ damper and the wind tunnel when a 24 by 24 damper with parallel blade operation is exposed to the flow disturbance from a horizontal louver that deflects the air upward. Most of the data points are outside the accuracy bounds.

Figure 47: Method 2 Correction for One Case shows the agreement between the same SpeciFlow™ damper exposed to the same louver flow disturbance after the Method 2 correction has been made. Now all of the data points greater than 300 fpm are within the accuracy bounds.

Figure 46: Impact of Upstream Flow Disturbance (Louver) on Accuracy

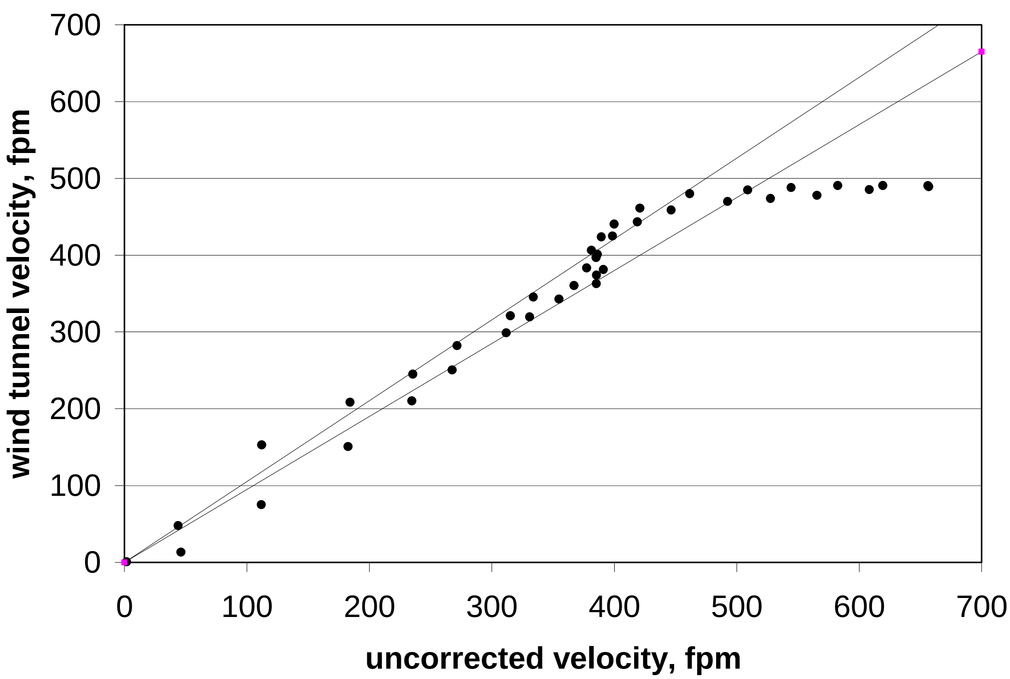


Figure 47: Method 2 Correction for One Case

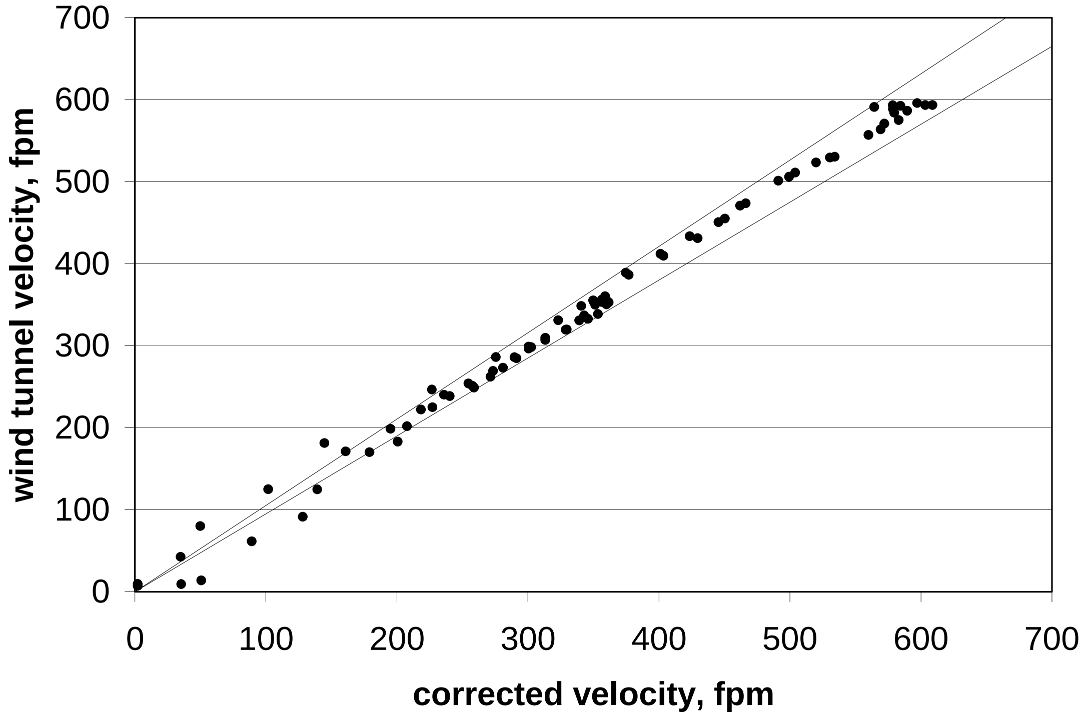
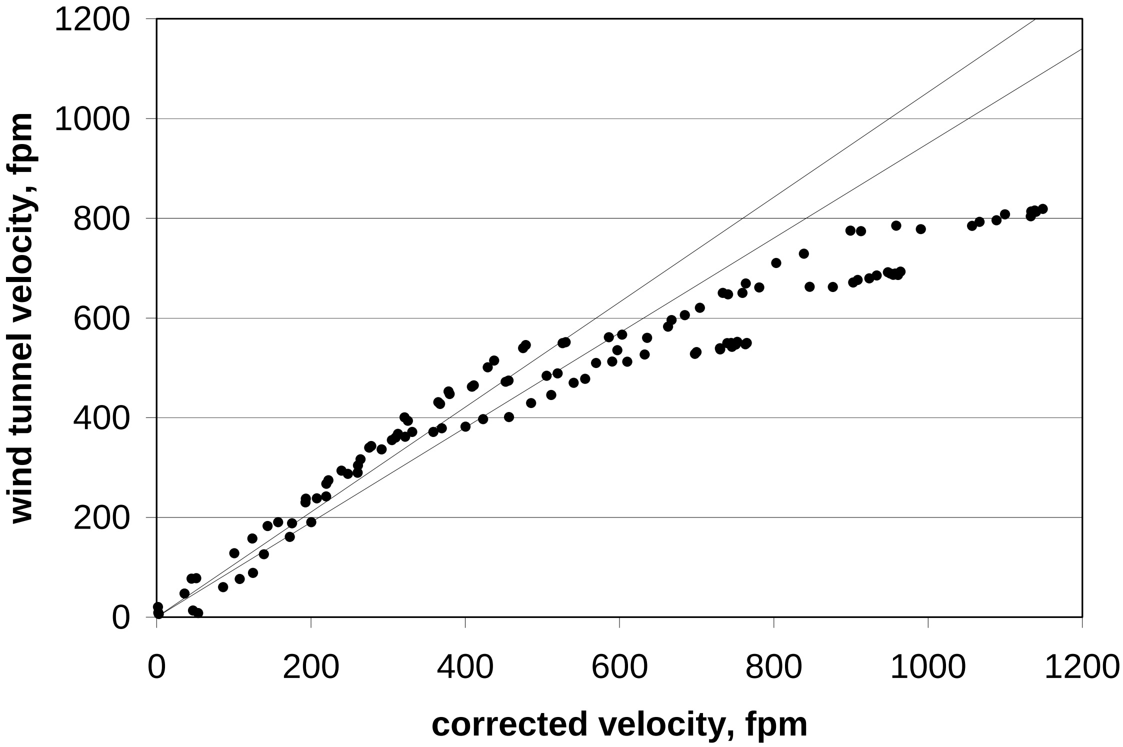


Figure 48 shows the agreement between the same SpeciFlow™ damper exposed to the same louver except that now the louver is turned upside down. The same correction is applied. Most of the points are again outside the accuracy bounds because of the asymmetrical behavior of the louver. A positive vertical pressure gradient caused by a louver deflecting air upward has a different effect on the flow coefficient of the damper than a negative pressure gradient caused by a louver deflecting air downward. This implies that it would be necessary to calibrate each damper five times in order to successfully use Method 2. There would be two corrections for horizontal non-uniformity (one for positive skew and the other for negative skew), two corrections for vertical non-uniformity, and the calibration for uniform flow.

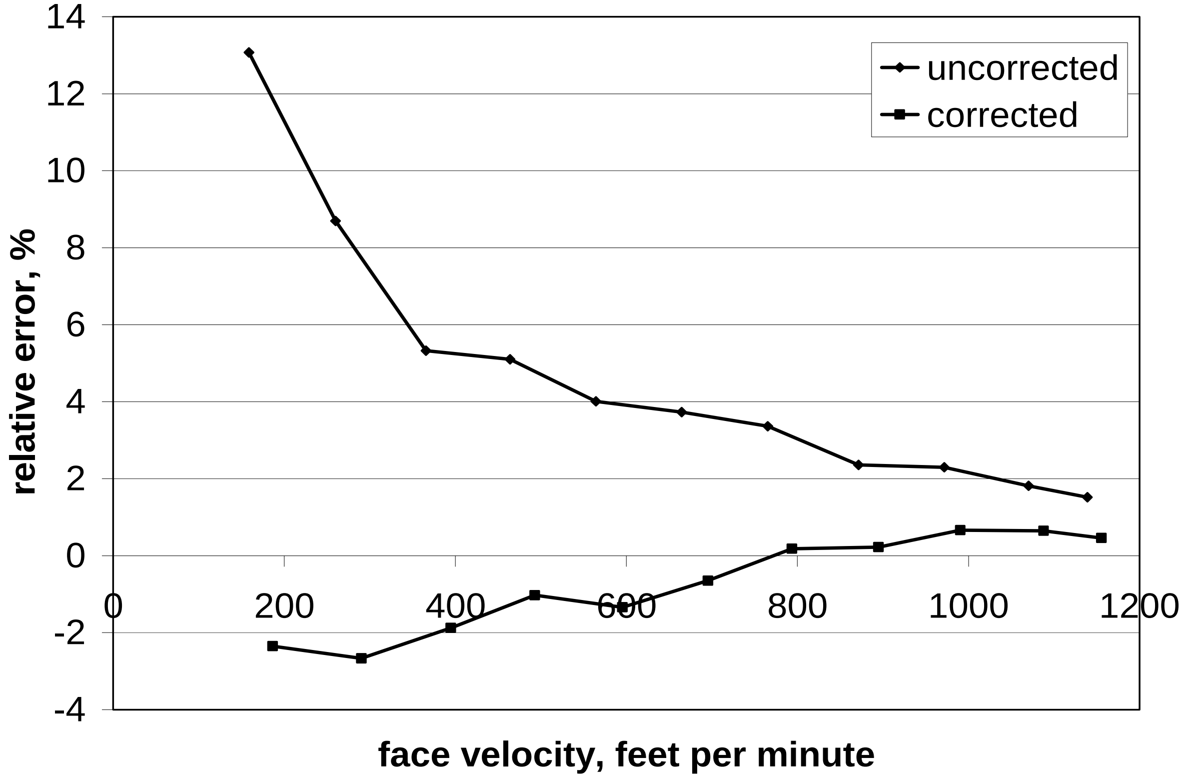
Figure 48: Method 2 Correction Applied to A Reversed Flow Disturbance



A positive outcome of Method 2 is demonstrated proof that if a SpeciFlow™ damper is integrated with a louver and calibrated with the louver in place, then there is no need for a flow straightener.

Non-uniform flow can be corrected effectively with a pressure sensitive flow coefficient.

Figure 49: Effect of Correcting for Velocity-Dependent Velocity Distribution



We found that both methods could be used effectively to correct for the changing velocity profile. However, it was computationally better to implement a pressure-dependent flow coefficient than a pressure-dependent exponent, so that is now the preferred method.

Figure 49: Effect of Correcting for Velocity-Dependent Velocity Distribution

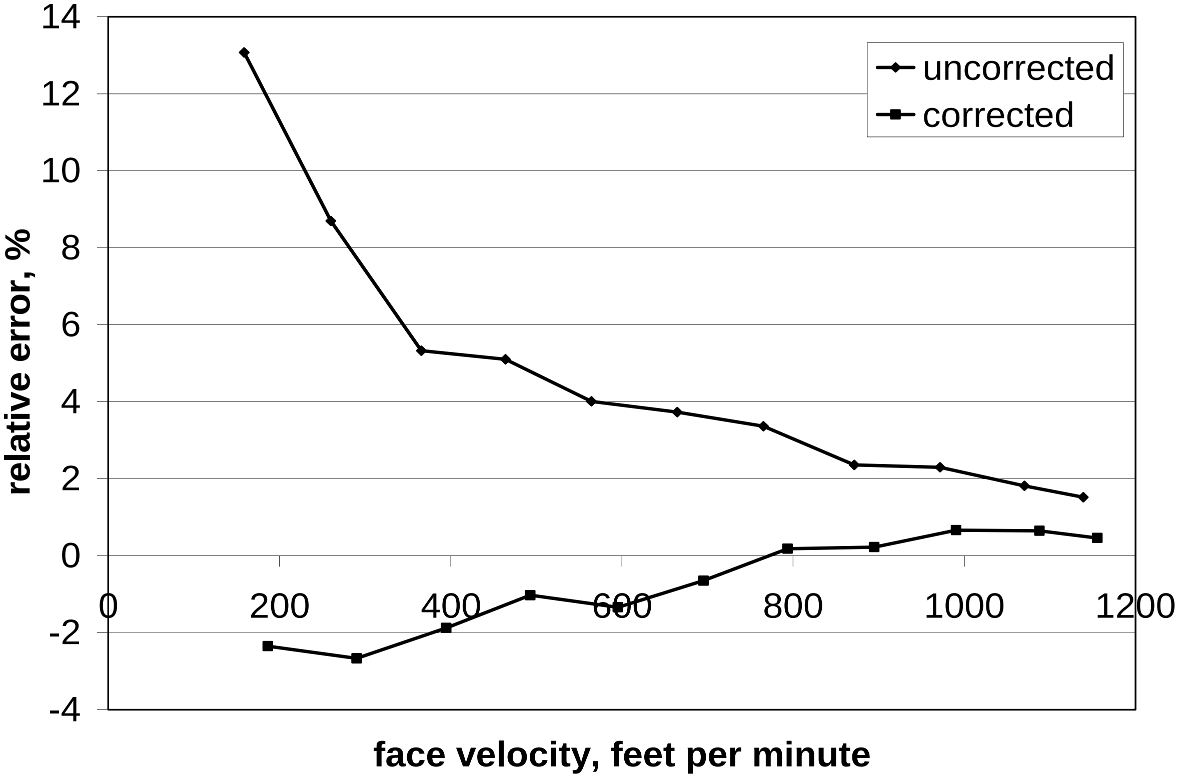


Figure 50 shows test data taken when a damper was at 100% open. In one case the flow coefficient is constant, and is chosen as the fixed value that produced the best agreement with calibration data taken over a wide range of average velocities. In the alternative case the flow coefficient is pressure-dependent, and the pressure dependence is optimized to produce the best agreement with the same calibration data. The results in the figure are for a new validation data set. For face velocities greater than 300 feet per minute, the largest error with the fixed flow coefficient is 7.4% of reading, and this error occurs at 300 feet per minute. With the pressure-dependent correction for the flow coefficient, the largest relative error is just 2.6% of reading, and this error also occurs at 300 feet per minute. Since the target accuracy is 5% of reading for readings greater than 300 feet per minute, these results clearly demonstrate the need for the pressure-dependent correction.

The control unit is an Excel 15 W7760C programmable controller from Honeywell, shown in

Figure 52. This controller is interfaced with a Honeywell S10010 direct-mount modulating actuator (

Figure 53) that is installed on the damper at the factory. The W7760C controller has eight digital inputs, eight digital outputs, eight analog inputs, and eight analog outputs. The analog inputs and outputs can be configured for voltage (0-10, 2-10, 0-5, 1-5 VDC) or current (4-20, 0-20 mA). The default configuration is 0-10 VDC. The W7760C controller has been programmed to implement the SpeciFlow™ application code using the LonSpec software. The base control configuration accepts inputs for position, pressure, and temperature from a modulating actuator, an external pressure sensor, and a thermistor, respectively. It provides analog outputs for damper position, flow rate, and temperature. Additional I/O can be added and used for custom control configurations. The controller can be interfaced with a building control system with either analog I/O or using the LONTALK® communications protocol on an Echelon® LONWORKS® network. The W7760C controller operates on 24 VAC from a Class 2 transformer. The controller provides 24 VDC power for an external pressure sensor. The controller, pressure sensor, and transformer are mounted in a steel NEMA 1 enclosure.

Figure 50: VCD-42 Control Damper.

Figure 51: Pressure Pickups on Damper Blade

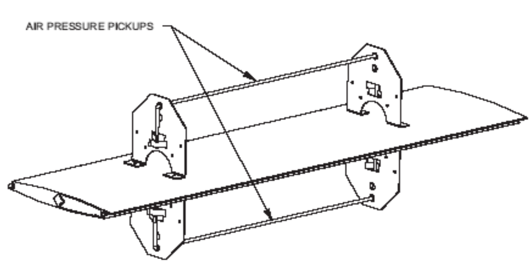


Figure 52: Excel 15 W7760C Controller

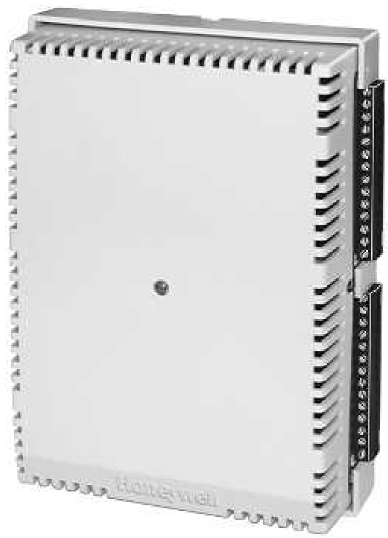


Figure 53: S10010 Damper Actuator

6.5 Conclusions and Recommendations

6.5.1 Conclusions

Most of the time manufacturing variability will be small enough to use a nominal calibration curve. The results also show that even when dampers have the same calibration curve (e.g., A and B), the small differences from damper to damper may cause the accuracy to be outside the specification when the damper is marginally open (e.g., 25% open). This is because the face velocities under these conditions are low even at the highest pressure that the pressure sensor can read. This implies that each damper must be calibrated at this position or at least checked for accuracy at this position prior to shipping.

A four-sensor array of pressure pickups arranged to average the velocity in each quadrant of the damper is inadequate for correcting for the non-uniform flow resulting from strong upstream disturbances such as louvers. This method of testing resulted in collinear results just outside the 5% error threshold up until the damper is opened 70% or more. These results can be fixed using weighted averages. The points collected after the 70% mark are not collinear and therefore cannot be fixed.

Two additional sensors used to measure the pressure gradient at the leading edge of a damper may be used to correct for non-uniform flow. However, separate corrections are necessary for each combination of direction (horizontal and vertical) and sign of the pressure gradient. This would increase the calibration effort by a factor of five, which would probably make this method more expensive than simply using a flow straightener.

A pressure-dependent flow coefficient can be used effectively to correct for the changes in the velocity distribution that are associated with changing average velocity between the damper blades. Two methods for effectively correcting the velocity profile were reviewed. Using a pressure-dependent flow coefficient is a better choice, computationally, than using a pressure-dependent flow exponent. Comparing a fixed coefficient to a pressure-dependent coefficient showed a large increase in accuracy from 7.4% error at 300fpm down to 2.6%, bringing the readings well within the 5% error margin.

The new SpeciFlow™ design incorporates all the recommended technical changes. Based on input from Greenheck and feedback from sales representatives, a list of upgrades to the design was compiled. The changes made were mostly I/O with the goal of making the design compatible to more systems.

6.5.2 Recommendations

Damper accuracy should be checked prior to shipping, particularly at marginally open positions. The results show that nearly identical dampers can use the same calibrations curves down to marginally open settings of 25% or less with high accuracy. At that point minor variances in the damper can lead to large errors in calibration so it becomes necessary to check the dampers before they are installed to verify that the generic calibration curve can be used.

Presently using pressure sensors in non-uniform flow environments is possible but not practical because of the 5 fold increase in calibration efforts. The most simple and cost effective cure for these conditions is to use a flow straightener.

CHAPTER 7:
Project 7: Market Connections

7.1 Introduction

This report presents the Market Connection component of the Advanced Automated HVAC Fault Detection and Diagnostics Commercialization Program (FDD) Public Interest Energy Research (PIER) program. The Program consisted of five FDD-related product development projects supported by the Market Connections component managed by New Buildings Institute (NBI) and the overall FDD Program management by Architectural Energy Corporation.

The FDD Program project areas and lead project developers were:

Project 1: FDD Program Administration (Architectural Energy Corporation - AEC)

Project 2: Web-Enabled Automated Diagnostics (AEC)

Project 3: AHU and VAV Box Diagnostics (National Institute for Standards and Technology -NIST)

Project 4: Advanced Packaged Rooftop Unit (AEC)

Project 5: Rooftop Unit Diagnostics (Field Diagnostics Services, Inc. - FDSI)

Project 6: SpeciFlow™ Technology (Federspiel Controls)

Project 7: Market Connections (New Buildings Institute - NBI)

The report serves two primary purposes: 1) to report the Market Connection activities and accomplishments within the FDD program, and 2) to provide the background and foundation for support of ongoing activities and recommendation that will lead to enhanced building energy performance and energy savings from the use of FDD products in commercial buildings of all types.

The report is organized into the following Sections:

Program and Project Goals – Provides the specific objectives of the FDD Program and the objectives of each FDD project.

Market Connection Goals and Task Status – Presents the market connection objectives and provides the documentation of the task-level activities and status of deliverables as outlined in the original scope of work.

Market Connection Results by Project – Describes the market connection activities relative to each technical project.

Market Connection Results by Area of Activity – Describes the market connection activities relative to the areas of impact.

Conclusions and Recommendations – Identifies the primary market perspective on the status of FDD products and presents recommendations for continuing to increase the market adoption and impact of FDD technologies to reduce energy use in commercial buildings.

7.2 Market Connection Goals

The objectives of Market Connection activity is to facilitate and accelerate the successful development and introduction of the advanced fault detection and diagnostic methods into commercial HVAC products that will be deployed in California buildings and promote the development of other equipment and techniques for the commercial market to improve indoor environments and energy efficiency. The Market Connections component was incorporated to help guide the market focus of the Program to increase the adoption and public benefits impact of the projects products and results.

Successful results were to include:

- Private sector adoption of technologies and practices from the Program.
- Regulatory and voluntary mechanisms that influence the integration of the results into the market and that exist as a result of this project.
- Accomplishments of main Market Connection tasks areas and deliverables described below.

7.3 Project Approach

7.3.1 Technology Transfer Plans

This task was designed to take the product developers through an initial business planning process parallel with the R&D process underway for the specific product. NBI provided a Technology Transfer Plan Template to each of the project teams. The Template had been previously developed for the PIER program to provide an effective means of preparing product developers to plan the path to market entry for their products. The Transfer Template included a comprehensive set of product- and market-related questions. In addition, the Template included a Business Case spreadsheet for estimating the potential statewide energy savings that might result from the FDD product penetrating its target market in California. The Template required the product developer to think through and provide:

- A product overview and development status
- The business case for the product in its market(s)
- Estimated potential customer, and statewide energy and demand benefits
- Market analysis
- Technology transfer options

Each product development team completed their template and submitted them to NBI staff for review. The templates were returned to each team for their response to NBI comments and resubmitted as complete. The ARTU template was completed at the end of the Program due to its specific circumstances.

7.3.2 Scoping Study

The completed Templates formed the basis for the Scoping Study and the scoring framework that was developed. The Study's objective was to provide assessments of the market strengths and challenges for the individual projects. The results of this Study were to be used to develop a Market Connection Plan that identified specific strategies and actions to increase the market adoption and penetration of the technologies and products being developed the program.

NBI established a set of criteria to assess the FDD technologies and practices, and focus on key areas known to affect the ability to successfully implement a technology or practice into the construction and energy efficiency marketplace, including into the codes and standards arena. The criteria were consolidated into four key areas:

- Energy and Economics
- Technology Performance
- Market Factors/Likelihood of Success
- Ability for Policy Change

Several national HVAC experts were selected to assess the strengths, uncertainties and challenges facing the candidate FDD products through a scoring exercise. Additional interviews were conducted with key persons within the HVAC private sector and in public state and regional energy efficiency market transformation organizations. These interviews were conducted to solicit expertise and discussion of the criteria pertaining to the technology or practice. The FDD program's Public Advisory Committee and the project teams reviewed a preliminary scoring matrix. Combining data provided by the project technical leads and team members with the knowledge and responses of the industry experts and scoring consultants resulted in the overall Scoping Study results.

The Study results indicated several common themes that impact all FDD products in terms of initiating Market Connections support. The consistency of feedback and scoring on these criteria indicates that they are priority areas for action in the Market Connections Plan. This Study found that all projects needed:

- Additional cost and energy performance information
- Determination of end user perceptions of value and acceptance
- Mitigation of real or perceived risk related to the actual use of the products in various markets
- Market leadership and demonstrated commitment from key market players in the private and public sectors
- Significant support from electric utilities and their regulators if the products are to be considered for standards and/or code adoption
- Solutions to market barriers common in each project would support commercialization of all the products.

Several overarching issues also emerged from the Study:

As emphasized by all respondents, the FDD products alone do not save energy.

Respondents all placed a heavy emphasis on the need for substantial training and technical support.

The degree and speed with which these products move toward commercial success will in large part be due to an informed market place.

There is a critical need to alter fundamental relationships and approaches within the commercial building market toward design/manufacturing/installation/maintenance practices that seek to continuously provide building owners and occupants with high performance operating conditions at the system and whole building level, over the life of the building.

A building energy performance-oriented approach must be strongly supported by the electric utilities, allied energy efficiency organizations and the regulators associated with building codes and the electric utilities.

All the FDD products in the Program had merit to save energy and improve indoor air quality, serve a variety of market needs and create business development opportunities for small, medium and large businesses. The individual product's potential strengths and challenges for market entry varied widely.

7.3.3 Strategic Partnership

The Program contract anticipated the development of signed partnership agreements with partner organizations. NBI staff engaged in information and communications on the Program, its products and FDD generally, directly to a number of individuals as well as to energy efficiency advocacy and industry organizations, including ACCA, ACEEE, ARI, ASHRAE, Bonneville Power Administration, the California Commissioning Collaborative, California Institute for Energy Efficiency, California utilities (IOUs and SMUD), Consortium for Energy Efficiency (CEE), Natural Resources Defense Council, Northeast Energy Efficiency Partnerships, Northwest Energy Efficiency Alliance, Northwest Power and Conservation Council, Northwest utilities, Portland Energy Conservation, and the Southwest Energy Efficiency Project.

Through AEC's active involvement in the CU/CSU Energy Efficiency Program, two Program products were demonstrated, Rooftop Unit Diagnostics-Project 5 and SpeciFlow Technology-Project 6.

CIEE staff was focused on metering approaches to building performance monitoring at higher subsystem and whole building levels, and did not choose to work specifically with the NIST FDD algorithms.

NBI staff will continue to directly carry the message of FDD within the building performance framework as part of its technical support relationship to the "Billion Square Foot Club," an energy efficiency advocacy group made up of large property owners nationally. NBI has received initial funding from the Energy Foundation to plan out the organizational development for establishing the Club. NBI, and its national network of technical contacts, will provide a wide and deep range of technical information and technical assistance on high performance building practices to Club participants. NBI will promote the outcomes of the collaboration to the entire property management business community through an active publicity campaign.

The opportunity to formally sign documents as called for in this Task did not fully present itself. Each of the organizations noted as well as others were supportive of the overall Program goals and were interested in specific Program products, but were not compelled to sign formal MOU's with NBI for the purposes of collaboration. MOU's may be useful under some circumstances, but were not a significant aspect in this Program.

7.3.4 Market Connection Activities

The major Market Connections work is reviewed within this task and encompasses a great deal of outreach and strategic intervention to maximize the potential for results. The activities are discussed broadly here followed by specifics for each product and then by area of influence or action.

The cumulative impact of Market Connections-related communications about the FDD program, its projects and FDD generally, has led to changes in market and regulatory perceptions about the usefulness of diagnostics in maintaining building energy efficiency. Specific impacts are described below.

NBI actively participated in the range of Program administrative activities including monthly Research Management Team phone calls, reviewing each project's monthly report, and delivering a monthly report on NBI's activities. NBI periodically reviewed individual project websites and provided feedback, kept material updated on the Program website www.archenergy.com/pier-fdd/, and discussed product development and Market Connections with the project teams on an ongoing basis.

NBI produced an initial product brochure for RTU Diagnostic-Project 5. The brochure (see Attachment 2) is distributed in print and on the company's product web site: http://www.fielddiagnostics.com/sentinel.htm. The product developer for Web Enabled Diagnostics and the manufacturing partner for SpeciFlow produced their own product promotional material.

There was no obvious national venue for displaying general FDD information in poster form. At some venues, there is no space allowance for product/program promotion. There is no national industry organization to promote FDD. As was clearly noted at the FDD Roundtable, FDD practitioners, providers and researchers saw no need for such a representative industry organization. FDD is in fact, rightfully part of the overall building performance framework and belongs more specifically in the building controls and maintenance areas, rather than viewed as a stand-alone subject.

Significantly, there is no national technical consensus or standard on what constitutes FDD for a specific class of HVAC systems, small and large. Although a description of the general characteristics of FDD might be describable in poster format, the basic principles of building performance management were generally known to the audiences at the events NBI staff attended. Individual project results (where available) were reported via presentations and in one-on-one conversations and smaller meetings.

7.4 Market Connection Results by Project

The following section provides a brief product progress and status with details on key Market Connections support activities for the individual Program projects.

7.4.1 Project 2: Web-Enabled Automated Diagnostics (AEC)

Early on in the Program, Architectural Energy Corporation (AEC) entered into an non-exclusive development partnership with Tridium, a global software and technology company, developer of the Niagara Framework®, a universal software platform that helps manufacturers develop Internet-enabled equipment systems and device-to-enterprise applications. This partnership was important in getting the first two commercial beta test sites for EBD. The product was still in development into 2007, limiting the amount of Market Connections support that could be provided given the need to prioritize the declining budget balance for Market Connections. The presence of AEC's existing extensive network of commercial (public and private) sector contacts through its PIER work and its private sector commercial services, should provide ample opportunity for potential marketing contacts for EBD.

Key Market Connections Activities:

Promotion. NBI initiated a nationwide two-hour webcast co-sponsored by the California Commissioning Collaborative (CCC). EBD was one of two FDD Program products featured.

Demonstration of Benefits. NBI continues to actively recommend EBD to Enovity LLC, the contractor for a PG&E program on assessing the benefits of FDD in helping to increase the persistence of energy savings following retro commissioning in large commercial buildings. http://www.enovity.com/programs/mbpcx.html

Marketing. NBI provided periodic review of the EBD website and suggested revisions. http://www.enformadiagnostics.com

Commercial Availability. The Enforma Building Diagnostic product is commercially available from AEC.

7.4.2 Project 3: AHU and VAV Box Diagnostics (NIST)

The National Institute for Standards and Technology (NIST) signed Cooperative Research and Development Agreements with several controls manufacturers including Alerton, Automated Logic Corporation (ALC), Delta Controls and Tour Andover. The manufacturing partners agreed to assist in commercializing the algorithms in their commercial products by translating the algorithms into their individual, proprietary control applications programming language. These programming libraries are provided without cost to the manufacturer's dealers for use in control specification. Of these potential partners, NBI was initially successful engaging in ongoing discussions with senior ALC and Alerton technical managers.

VPACC was installed in the Philip Burton Federal Building in San Francisco in 1200 VAV boxes. NBI produced a Case Study of the use of VPACC in this building that is posted on the FDD

Program website. The fault detection outputs are integrated with the building's computerized maintenance management system. The system issues work orders to the facility's maintenance staff to respond to detected faults, most of which are resolved through control system adjustments. The fault detection is proving so beneficial to maintaining system performance that a senior General Services Administration official in federal building management in federal Region 9 intends to install VPACC in all federal facilities where possible, including the new federal building in San Francisco. NBI strongly urged installation of VPACC and APAR to Enovity, the contractor managing the PG&E retro-commissioning persistence program. At least three additional existing state and federal facilities in California will have VPACC and/or APAR installed as part of the PG&E program.

The following table shows sites with APAR and VPACC installed or *planned for 2008.

Table 14: APAR and VPACC Installation Sites

Sites	Location	# AHU	# VAV
Office/Laboratory	Richmond, CA	4	
Office Building*	San Ana, CA		200
Office Building	San Francisco, CA	2	1200
Office Building*	San Francisco, CA		200
Office Building*	San Jose, CA		270
Office Building	Atlanta, GA	2	53
Research Campus	Gaithersburg, MD	3	
Campus Building	Takoma Park, MD	2	101
Office Building	Las Vegas, NV	2	2
Museum	Boalsburg, PA	2	9
Office Building	Harrisburg, PA	18	
Office Building	Shippensburg, PA	1	47
Office Building	Redmond, WA		28

The adoption of the NIST algorithms by the Iowa Energy Center[3] set in motion a legal challenge from JCI[4] that created a significant barrier to the strong market momentum that was underway for this FDD product. ALC in particular, chose to back away from integrating the NIST

[3] In 2006, the Iowa Energy Center issued a specification for a controls system upgrade in its facilities that would include APAR and VPACC in order to test the algorithms in terms of energy and indoor air quality benefits and to use them as a teaching/training tool. This would have been the first fully commercial bid for use of the algorithms. The Energy Center received notification from JCI threatening legal action if the algorithms were used.

[4] JCI held meetings with NIST, claiming existing global patent rights on the use of moving weighted average algorithms at the device controller level. JCI does not incorporate this fault detection approach at the device controller level in its products. NIST attempted without success to work out a deal with JCI, since it believed that the development of the algorithms pre-dated JCI patent claims. The negotiations were inconclusive. Neither side has chosen to proceed legally.

algorithms into its products and widely promoting them. This is all very unfortunate, since the algorithms provide a low cost, effective fault detection tool that could have resulted in far more widespread market adoption, especially with the attention that ALC was giving to integrating it into its main controls product line. Also unfortunately, JCI does not yet implement this FDD approach in its own products.

Although the legal situation is murky, NIST staff will continue to provide information as well as the line code version of the algorithms upon request. The CEC has not been directly contacted by JCI. It is expected that the planned sites for installation of APAR and VPACC in additional state and federal facilities in California will go as planned. It is not known whether Johnson Controls is aware of these installations. Recently, Alerton has incorporated the algorithms to some extent in new control products.

Key Market Connections Activities:

Codes and Standards. NBI staff collaborated with Energy Soft LLC staff to substantiate the benefits of having FDD capabilities in built up HVAC systems adopted by the CEC in the 2008 revision of the Title 24 Nonresidential Building Standards as Compliance Options. Compliance Options allow project developers access to additional compliance points to meet code point requirements. NBI and Energy Soft submitted a final joint proposal to CEC to adopt Diagnostics for AHU and VAV Boxes along with information on benefits along with a proposed change in the Alternative Compliance Manual to account of the presence of FDD. The FDD Standards proposal is in the final stage of public comment on the 2008 revision. It is likely the proposal will be adopted. This is an historic and significant positive impact for sending an initial signal about FDD and its potential value to the market in terms of improved building performance, as well as leading toward future FDD requirements in Title 24.

Market Awareness. NBI supported development of a Case Study of the use of VPACC in the Philip Burton Federal Building in San Francisco that is posted on the FDD Program website.

Promotion. The FDD algorithms were one of two FDD Program products featured in a nationwide, 2-hour webcast initiated by NBI and co-sponsored by the California Commissioning Collaborative (CCC).

FDD Tool Development. NBI requested and supported the translation of the FDD algorithms into Johnson Controls Metasys programming code.

FDD Tool distribution. NBI distributed the NIST algorithms and the Metasys version to a variety of interested parties.

Demonstration of Benefits. NBI has actively recommended AHU and VAV box algorithms to Enovity LLC, the contractor for a PG&E program on assessing the benefits of FDD in helping to increase the persistence of energy savings following retro-commissioning in large commercial buildings. http://www.enovity.com/programs/mbpcx.html The planned sites in Richmond, Santa Ana and San Jose, are coming through the PG&E program.

7.4.3 Project 4: Advanced Packaged Rooftop Unit (AEC)

Market Connection activity on this project was focused on working with CEE to determine interest in CEE utility members nationwide in developing a program within existing demand side management programs, to implement a market education and financial incentive approach to the ARTU. Based on the ARTU Benefit-Cost Report[5] NBI and AEC approached CEE's HVAC Committee to propose a Voluntary Initiative in support of the ARTU. The proposal was accepted and NBI made a presentation at the CEE annual Industry Partners meeting in September 2007 on the elements of an Initiative. CEE is working with member responses to begin to develop a program framework.

The key goal is to create market interest and demand from building owners and HVAC contractors for these features, rather than trying to directly influence HVAC manufacturers to incorporate the ARTU features across all product lines rather than only in the relatively small number of high tier units that they currently sell. The addition of utility incentives for a package of ARTU features, yet to be determined, would help put the ARTU into the range of customer interest.

Manufacturer Networking. NBI presented the ARTU project as part of the NBI webcast to ARI Unitary Large and Small Committees. NBI circulated the ARTU Features Definition Report through ARI to the entire HVAC industry as well as to individual companies.

Product Development. NBI is in discussions with Honeywell product development managers on incorporating ARTU features in a new economizer controller under development.

Utility Market. NBI and AEC's proposal to CEE to begin development of a Voluntary CEE Initiative was accepted. NBI promoted the ARTU features to the utilities in California, the Northeast and the Northwest individually and in groups.

7.4.4 Project 5: Rooftop Unit Diagnostics (Field Diagnostic Systems, Inc.)

This monitoring and remote web-based communications capability of the ACRx Sentinel represents the state-of-the-art of FDD for commercial unitary HVAC units 5-50 tons. This market is huge and in need of a wider range of automated diagnostic tools to help maintain equipment operating performance. Embedding the additional required sensors, data processing and communications hardware in new units by an HVAC equipment manufacturer clearly provides the best business case for the product.

The company has been in discussions on and off with OEM HVAC companies and HVAC service companies about adopting the Sentinel technology, but no deals have yet been signed. A potentially key channel for the Sentinel for both retrofit and new markets is through partnership with a large HVAC service organization with a large number of facilities under performance management. It is likely that only high tier HVAC contractors would provide this level of sophisticated proactive service to relatively few customers.

Product development work has continued throughout the Program. This has had the impact of limiting market interest in what was viewed as an incomplete product. The company's last

[5] Completed in July 2007 by Portland Energy Conservation, Inc. (PECI)

major task under the Program is to implement up to 60 systems for the final field test of the first complete product build. The field test is expected in 2008.

FDSI has one potential competitor for this type of FDD system with remote communications to a web-based UI. Researchers at PNNL along with industry partners, are working to deploy a similar FDD system for rooftop units. PNNL has secured funding to deploy up to 225 systems in Washington State in 2008.

NBI staff provided significant Market Connections support for this product and will continue to support market entry of the Sentinel through our ongoing activities in promoting high performance commercial buildings. As the interest in high performance buildings and measured performance grows, the market will grow to recognize the obvious need for this level of diagnostic functionality in building operations.

Key Market Connections Activities:

7.4.4.1 Product Development

NBI visited with FDSI at its office in Pennsylvania to consult with the company's CEO, President, and marketing and technical staff on a number of product development, UI and marketing issues.

7.4.4.2 Marketing Materials

NBI provided a needed boost to FDSI's marketing efforts by preparing the first Sentinel promotional brochure.

7.4.4.3 Product Development

NBI provided a conceptual product package design (see Attachment 3).

7.4.4.4 Title 24 FDD Proposal

NBI solicited materials from FDSI staff on FDD energy savings data for the 2008 Title 24 unitary HVAC FDD Compliance Option proposal. These materials were instrumental in showing that the proposed unitary FDD Compliance Option would result in energy and demand savings.

7.4.4.5 Manufacturer Meeting

In 2006, Lennox Industries, for the first time, invited a small group of outside individuals actively in involved in HVAC efficiency work to the Lennox Market Leaders Summit. The outside participants were there to discuss ideas and insights with Lennox staff on issues that were of concern to efficiency advocates and those working in utility HVAC programs. NBI staff was invited to participate through its work both on the FDD Program and on another PIER program, the Hot Dry Air Conditioner Project.

Following the Summit meeting, NBI staff presented an extensive run through of the on-line Sentinel UI with Lennox staff including: Director of Controls Product Management; Platform Leader Controls; Product Manager of Commercial Controls and Aftermarket Products; Team Leader of Cooling Product Development and R&D; and Product Manager of Commercial Rooftop Products. While Lennox has shown interest in the FDSI product and has held subsequent discussions with FDSI, a formal business agreement has not yet been reached.

7.4.4.6 Industry Presentations

NBI presented a walk-through of the on-line Sentinel UI at the ESource Forum, CEE Industry Partners Meeting and for the PNW utilities rooftop unit working group. In addition, NBI communicated product features to the Northwest representative of the national Kroger Grocery store chain, Target Stores Research Manager and Wal-Mart's Director of Engineering, Prototype and New Format Development.

7.4.4.7 Utility Testing

NBI recommended the testing of the Sentinel on a rooftop unit through the PG&E Emerging Technology program. PG&E staff at the San Ramon test facility is working to identify an RTU site for testing the Sentinel.

7.4.4.8 Regional Outreach

NBI recommended purchase and demonstration of Sentinel systems to the Northeast Energy Efficiency Partnerships and to a regional utility working group in the Pacific Northwest. Potentially interested parties wanted a finished unit rather than a demonstration model still in development.

7.4.4.9 Commercial Availability

The Sentinel may be available commercially for retrofit application by the fourth quarter of 2008, although availability will depend in part on the outcome of the expanded field demonstration.

7.4.5 Project 6: SpeciFlow™ Technology (Federspiel Controls)

The Greenheck sales manager reports that he is satisfied with commercial progress having met its sales goal of 100+ units the first full year of the product's availability and is expecting to meet similar sales goals for the coming year. The key to product sales has been the one-on-one relationships between vendors and potential customers rather than promotional advertising.

Units were installed through AEC and the CU/CSU Energy Efficiency Program at UC Santa Barbara and CSU at Stanislaus. AEC staff compiled a photographic record of the installation process.

ESource provided a two-page description of the SpeciFlow technology for public distribution through the CEC. http://www.esource.com/public/pdf/cec/CEC-TB-21_SpeciFlow.pdf

Key Market Connections Activities:

Promotion. NBI provided a list of major energy- and contractor-related trade publications for use by the product developer for press releases he wanted to develop and distribute directly.

Market awareness. NBI staff sent descriptions of the product to a range of professionals and companies.

Manufacturer Support. NBI conversations with senior Greenheck marketing personnel indicated that they would develop marketing and case study materials as appropriate and might provide suggestions to NBI as how it might assist in marketing efforts. NBI has not received further guidance from Greenheck or the product developer on supporting this product.

Commercial Availability. The SpeciFlow technology is commercially available from Greenheck Fan Corporation as the "IAQ-42."

7.5 Market Connection Results by Area of Activity

During the course of the Market Connections work, significant opportunities arose that NBI was able to respond to with the financial resources that were available through the Program. These opportunities all have had significant positive state of California impacts and are described below based on the area of activity and impact.

7.5.1 Regulatory

Opportunities to incorporate technologies and practices into regulatory mechanisms create lasting impact that can be leveraged to increase implementation of the emerging FDD products. For the PIER FDD Program there were two primary venues for regulatory adoption of the research results – Title 24 Building Standards, and the California Utility Commission's (CPUC) Big Bold Energy Efficiency Strategy public process that was initiated in 2007.

7.5.2 Codes and Standards: California Title 24 Nonresidential Building Standards

In 2006, PIER management staff requested that a contractor review PIER program activity for potential items that might be considered for proposing into the 2008 revision process for the California Title 24 Building Standards. The contractor, Martyn Dodd of EnergySoft, LLC, reviewed the overall PIER program and identified two specific projects from the FDD Program: 1) Project 3 - AHU and VAV Box Diagnostics and 2) Project 5 – RTU Diagnostic. EnergySoft submitted two draft 'Measure Information Templates' to CEC for consideration: Fault Detection and Diagnostics for Air Handling Units and VAV Boxes, and Fault Detection and Diagnostics for Rooftop Air Conditioners. Although NBI was initially unaware of the submission, EnergySoft soon contacted NBI and we began to work closely for a more comprehensive final submission that was made to CEC in 2007. NBI staff provided substantial background material for the final submission of both templates to CEC. NBI staff attended the July 2007 public workshop on the 2008 Standards revision, prepared to respond to questions. NBI staff entered a brief comment into the record on the potential adoption of the FDD provisions, thanking the Commissioners and Commission staff for their consideration and support of these forward looking measures.

The two submissions have been open to public review and comment for two years since the initial proposals were made. NBI solicited written comments to CEC from ALC, FDSI, Honeywell, FDD researchers, Enovity, the O&M and commissioning contractor for the San Francisco Federal Building, and the GSA Region 9 senior facilities manager. There was only one significant public comment opposing the inclusion, with the principal argument that there was insufficient energy savings data to support the proposed inclusion in the Alternative Calculation Method Manual. The overall usefulness of the FDD approaches proposed was not in question by the commenter, although it is true that there is insufficient detailed information on the direct energy and demand benefits of FDD at this time to send a clear signal to the buildings marketplace. The two FDD proposals were submitted as 'Compliance Options' not as code requirements, since there are a number of other conditions that a requirement would have to meet in addition to establishing energy savings benefits.

In June 2007, NBI staff attended a CEC public workshop on R&D proposals for the 2011 Title 24 revision process and proposed FDD inclusion in the R&D process. Although FDD did not make the initial top R&D prioritization by CEC staff, support for establishing FDD requirements in the 2011 Title 24 revision surfaced in the CPUC Strategic Plan recommendations. The future goal of proposing FDD in some form(s) as a code requirement for the 2011 Title 24 revision process will only be possible if sufficient information on the commercial availability, effectiveness, costs and energy/demand savings of FDD technology is available for CEC consideration. Currently, there is no formal follow-up yet planned by PIER to establish FDD energy and cost savings benefits or FDD standards. The CPUC has recommended extensive follow up on establishing FDD benefits through the IOU Emerging Technology program, as well as other utility and market approaches.

As of the January 30, 2008, and the initiation of the CEC final 15-day public comment on the proposed 2008 revisions, the two FDD Compliance Option measures were included in the Alternative Calculation Method Manual and will appear in the 2008 Title 24 revision.

CPUC Big Bold Energy Efficiency Strategy Workshops

NBI staff participated in the CPUC Big/Bold Energy Efficiency Strategies" Workshop Series in June 2007 and assisted in the facilitation of the HVAC breakout group. In the draft "Recommended Strategic Plan to Transform the Existing HVAC Industry and Achieve Additional Peak Savings, Sustainable Profitability, and Increased Customer Comfort"[6] released in January 2008, the HVAC Vision section contains support for:

"Innovative system manufacturers must be encouraged to compete to deliver reliable, high comfort, space conditioning systems equipped with features that simultaneously minimize peak energy use and overall costs to the customer. Incentives should be provided to manufacturers who work to <u>integrate smart diagnostic systems into the original cooling system equipment to provide useful fault detection information to contractors and suggested actions to minimize usage to customers."</u>[7]

In addition, the HVAC Strategy notes:

"Support commercialization of <u>on-board and portable diagnostic and fault detection systems.</u> Stimulate existing research to <u>integrate on board diagnostic equipment</u> into new central air

[6] http://www.californiaenergyefficiency.com/docs/hvac/HVAC Draft 1-5-08.pdf

[7] pg. 5, item 4.

conditioning systems and to develop better portable diagnostic equipment that could be used to simplify maintenance and repairs."[8]

The document cites the HVAC Roundtable (described below), organized by NBI, in the following section:

"Strategy 7: Support commercialization of on-board and portable diagnostic and fault detection systems."[9]

California investor-owned utilities have jointly filed a draft plan[10] in response to the CPUC process that will be followed by a final plan in May 2008. NBI staff will provide formal comments on the utility draft. The draft contains the HVAC Sector strategy diagnostic recommendations referenced above. The Appendix to the plan also contains the summary notes from the NBI initiated HVAC Roundtable.

NBI's ongoing networking and communications to individuals and organizations represented in the CPUC process led to specific action recommendations on FDD in the Strategic Plan.

7.5.3 Utilities

NBI explored entry into the California utilities Emerging Technology (ET) and Savings By Design programs for FDD products. NBI was successful in recommending to PG&E that the FDSI Sentinel be tested. PG&E staff are in the process of identifying a suitable site near the PG&E San Ramon test facility. NBI was less successful in working with PG&E staff to have the AHU/VAV Box Diagnostics installed in PG&E's Pacific Energy Center. In the absence of substantiated cost and savings benefits, FDD could not be implemented through the Savings By Design channel.

NBI staff are managing a research project on rooftop unit service protocols for utilities in the Pacific Northwest and in the Northeast, including the Northeast Energy Efficiency Partnerships and the New York Energy Research and Development Authority. NBI staff have established a working relationship with Honeywell, specifically with the Product Manager for Honeywell economizers and related sensors who was a member of the FDD Program Public Advisory Committee. In addition to working with this utility group on a solution to a serious problem with a ubiquitous Honeywell economizer controller, Honeywell asked for recommendations related to a new economizer design that is in development. NBI staff focused Honeywell staff attention on the ARTU specifications for incorporation into their new design.

NBI has incorporated features of the ARTU and Rooftop Unit Diagnostics into its Advanced Buildings Core Performance Program. Advanced Buildings is a suite of prescriptive energy efficiency measures designed to result in new commercial buildings up to 70,000 sq.ft. with

[8] pg. 5 item 7.

[9] pgs. 21-22.

[10] http://www.californiaenergyefficiency.com/docs/plancomments/DRAFT CEESP--FOR SERVING 02-08-08.pdf

energy performance 20-30% better than the ASHRAE 90.1-2004 energy standards. The Advanced Building program is being offered by a number of utilities in New England, including Efficiency Maine, Efficiency Vermont, National Grid and NSTAR. The Energy Center of Wisconsin will be offering the program statewide in 2008. Efficiency New Brunswick (Canada) is reviewing program adoption.

ARTU economizer features are incorporated as Core Performance Requirements. A section on FDD is included as part of the Enhanced Performance Strategies (see report 7.1). The Core Performance program is currently the only prescriptive approach without building modeling requirements eligible for Energy & Atmosphere Credit 1 points under the US Green Buildings Council's LEED program.[11] Following the Core Performance Requirements provides 3 EAc1 points. Additional points are available for selecting up to six Enhanced Performance Strategies. In addition, the Core Performance subscriber-based Reference Materials website strongly recommends consideration of all ARTU features including FDD when specifying and purchasing HVAC equipment.

7.5.4 Networking and Collaboration

7.5.4.1 FDD Roundtable

In June 2007, NBI staff initiated and organized an FDD Roundtable with substantial support from Western Cooling Efficiency Center staff. The initial goal of the Roundtable was to develop a Roadmap with an Action Plan for California that would result in increased recognition and use of fault detection and diagnostics in HVAC equipment and systems in the state's commercial buildings sector. The two specific planned outcomes were:

- Development of Action Items that addressed the current barriers/challenges facing FDD in the marketplace, with commitments to follow up.
- Identify opportunities for collaborative efforts on behalf of FDD in California and elsewhere to support FDD in a variety of commercial building markets.

Thirty-one participants from California, the United States, and Canada met at the University of California at Davis for a day-long working session. NBI prepared a summary of the technical, performance/value, and market awareness challenges that have been identified by FDD practitioners and researchers. Participants then broke into small groups to develop priority strategies and actions to address each of the challenges.

In brief summary:

- The use of and benefits of FDD cut across several major market segments including: building owners, building managers, facility operators, building controls vendors and specifiers, HVAC service companies, O&M contractors, the commissioning industry, utility companies, carbon emissions agencies, and probably others. It is vital to get the message about FDD across these markets since FDD application and benefits have specific appeal depending on the market.

[11] https://www.usgbc.org/ShowFile.aspx?DocumentID=3198 See Option 3.

There is no national champion (individual/organization) *per se* that is leading efforts to move FDD further into the market. It is not clear where such a champion might come from, if one were to emerge. There was no specific interest among participants in establishing a national organization to represent FDD in a variety of stakeholder venues. Yet without a person or organization at the center of FDD, collaboration/cooperation in support of FDD is left to enterprising interests and is generally a random event.

A statewide collaborative FDD work plan should be developed for the California Energy Commission and the California utilities that would potentially address the Roundtable Action Items as well as related activities. This might provide a more effective and consistent approach to providing timely responses to the known technical, performance/value demonstration and market awareness challenges facing FDD.

There were several action items developed at the meeting including an ASHRAE Research Topic Assistance Request on a FDD graphic user interface found at http://www.taylor-engineering.com/Dashboard/ and a summary of FDD benefits from use of the PACRAT FDD tool from Facility Dynamics, that are being actively worked on. From the Roundtable invitation list, NBI has compiled an 80 person mailing list to notify participants of new FDD research, policy and commercial product related developments.

Two key action items were identified for specific follow up in California:

1. Investigation of Best FDD Practices
2. Survey of Cost/Benefits of Existing FDD Demonstrations/Field Sites. Based on the Roundtable results and ongoing discussions with NBI staff, WCEC staff developed a proposal to the California investor-owned utilities to pursue these action items (see Attachment 6). This is a major step forward in support of market adoption of FDD and is a direct outcome of the NBI initiated FDD Roundtable.

7.5.4.2 HVAC Roundtable

Through ongoing networking on FDD and related HVAC topics, NBI staff became aware of a number of related fundamental technical questions that have been raised by HVAC industry professionals over several years and that remain unresolved. These issues have a direct relationship to the potential for achieving substantial, cost-effective, and persistent energy and demand savings from the operation of utility-sponsored residential and commercial HVAC service programs in California, as well as nationally. NBI staff concluded because of the cross-cutting interests involved, that there was no obvious state- or national-level forum for a discussion on the merits of the topics and for resolution of the issues being raised. To attempt to respond to these issues, NBI staff, with AEC staff support, organized a national HVAC Roundtable in October 2006 held in Oakland, California.

Representatives from HVAC service contractors, ARI, Carrier Corporation, California utilities, CEC staff, university researchers, FDD tool developers, and others were invited for a 1.5 day facilitated workshop to discuss and attempt to resolve as possible the issues initially raised. As a result, a letter was drafted to ARI requesting an industry response to the issues raised. Although the letter has not been formally transmitted to ARI, PIER is providing support for two of the key action items voiced by the participants: 1) expansion of the range of in-field unit refrigeration charge diagnostic protocols down to 50°F outside temperature, 40°F degree wet-bulb, with an upper limit of 115°F outside. PIER's Building Energy Research Grant program has funded FDSI to conduct the analysis, and 2) the establishment of a national benchmark protocol for refrigeration charge checking. PIER is considering funding Dr. James Braun of Purdue University to develop the charge diagnostic benchmark protocol as well as a residential HVAC diagnostic tool. Five of the ten recommendations from the Roundtable participants were related to FDD. The CPUC noted these in its HVAC Sector Strategy.

The other issues raised by Roundtable participants will be included in a list of issues being developed for a paper accepted by the American Council for an Energy Efficient Economy 2008 Summer Study regarding the need for a National Cooling Initiative designed to address these and other issues related to the future of compressor-based cooling. In addition, the Roundtable issues were submitted to a proceeding underway at the US Department of Energy on planning for future DOE HVAC programmatic initiatives for achieving zero energy buildings and the part that cooling and heating technologies have to play.

7.5.4.3 ASHRAE FDD Seminars

NBI staff made a proposal to the ASHRAE Technical Committee (TC)7.5 - Smart Building Systems: Fault Detection & Diagnosis Subcommittee, to hold an FDD seminar at the ASHRAE annual meeting in 2006 to promote the FDD projects in the Program and FDD in general. TC7.6 - Systems Energy Utilization: Monitoring & Energy Performance Subcommittee and TC1.4 Controls Theory and Applications joined as co-sponsors. FDD Program Projects 3 and 5 were presented by three presenters from different perspectives: the Chief Engineer of the Phillip Burton Federal Building (San Francisco) for Project 3, a representative of the Iowa Energy Center for Project 3, and a representative of the Honeywell Global Service Response Center for Project 5. Sufficient interest in the topic was created to add a second FDD seminar to cover more ground. NBI staff helped identify presenters for both seminars including a representative of PG&E, organized the submission of the seminar abstracts to ASHRAE and chaired the first seminar. Over 100 people attended both seminars.

NBI staff attended one subsequent meeting of the TC7.5 FDD subcommittee to explore the issue of an FDD specification. The subcommittee was focused on two projects 1) the benefits of FDD and related unit field servicing in unitary rooftop systems, and 2) development of a statistically-based chiller diagnostic. Although there was great interest in overall FDD issues, there were limited resources among subcommittee members for tackling other FDD issues, including the development of a minimum specification for FDD capabilities in both unitary and built up HVAC systems.

In a related matter, in September 2007, NBI staff was asked by a member of the ASHRAE 90.1 Standards Committee if there was anything that could be immediately proposed to the Committee on FDD, especially with regard to energy savings benefits. The answer was not a simple one. There are several studies of FDD and energy savings in unitary HVAC systems, but none of the studies is comparable since each one uses a different set of FDD features in the analysis. Without an agreed upon minimum FDD specification, the quantification of FDD energy savings benefits across HVAC system types will be difficult to establish.

7.5.4.4 FDD Webcast

In collaboration with the CCC and AEC, NBI organized a national webcast on FDD to showcase Web Enabled Diagnostics (AEC's Enforma Building Diagnostic tool) and AHU and VAV Box Diagnostics (NIST). Presenters included:

Mark Levi, General Services Administration Region 9 (AHU-VAV Box Diagnostic Algorithms)

Jeff Schein, NIST (AHU-VAV Box Diagnostic Algorithms)

Jonathan Soper, Enovity LLC (AHU-VAV Box Diagnostic Algorithms)

Stuart Waterbury, Architectural Energy Corporation (Enforma Building Diagnostics)

Jeff Strickland, Western Building Services (Enforma Building Diagnostics)

There was follow up interest from two ALC controls dealers in California. They were contacted and provided with the information they requested on the algorithms. Eventually, they were impacted by the ALC corporate decision to halt use of the algorithms due to the Johnson Controls legal threat.

7.5.4.5 Western Cooling Efficiency Center

NBI is a member of the Steering Committee of the Western Cooling Efficiency Center (WCEC), which is a component of the Energy Efficiency Center at the University of California at Davis. WCEC's mission is focused on identifying technologies, disseminating information and implementing programs that reduce cooling system electrical demand and energy consumption in the Western United States.

NBI has provided all appropriate materials from the FDD projects to WCEC staff related to Rooftop Unit Diagnostics and the ARTU for considering in WCEC work activities. The Center's upcoming Western Cooling Challenge project that is seeking a high EER commercial cooling unit for hotter drier areas of the West, will consider Rooftop Unit Diagnostic capabilities and ARTU features as part of the required specification.

As noted, WCEC staff supported the FDD Roundtable and subsequently developed a comprehensive statewide comprehensive proposal to assess and promote the benefits of FDD, establish minimum FDD protocols and educate building owners on use of these performance management tools.

7.5.5 Building Benchmark/Diagnostic Tool

Discussions with staff knowledgeable about FDD and building operations at Portland Energy Conservation, Inc. (PECI), led to a convincing observation that building operators were already so overwhelmed dealing with day-to-day building operations issues that adding an FDD layer on top of their existing responsibilities would not be useful or effective. PECI staff believed that there was a compelling need for other tools that could be used to establish building performance benchmarks in larger buildings with built up systems, which would in turn help building operators identify operating faults and provide performance tracking in subsystem components. The tool would also be useful to commissioning and retro-commission providers. It is useful to note that commissioning and retro-commissioning are inherently forms of diagnostics, typically not embedded or automated, but having potentially significant impact on building operating performance.

The initial tool development effort was being supported by the PIER program. NBI provided a small amount of additional financial support for the tool development, which had the impact of leveraging a larger cost share from the Northwest Energy Efficiency Alliance. The tool is not a primary product of the FDD Program. NBI staff were part of the tool project advisory committee. Detailed information on the tool as well as the tool itself, Energy Charting and Metrics (ECAM), will be publicly available at the CCC Commissioning Tools and Templates site. NBI will also promote the tool through its Advanced Building program.

7.5.6 Publications

NBI staff proposed an article on the NIST algorithms to HPAC Engineering Magazine "Control Freaks" column. It was published in February 2006. HPAC Engineering has a readership of 57,000.
http://www.hpac.com/ColumnBs/ControlFreaks/Article/24441/Fault_Detection_and_Diagnostics

At the same time, the Building Commissioning Association requested an article on the NIST algorithms for its Checklist Newsletter that is distributed to its national mailing list of over 1400 commissioning practitioners. The content was very similar to the HPAC article, with a slant toward value of the tools by commissioning providers.

7.5.7 FDD Website

NBI staff asked several leading FDD professionals about where on the World Wide Web they would refer someone to find FDD information at a central location. The uniform response was: "there is no such place." NBI approached three organizations that might be appropriate for hosting such a site. None of organizations was able to take on the task without additional funding. NBI has decided to establish an FDD site on its own www.GettingToFifty.net website that focuses on high performance buildings. The site will contain some annotation, but primarily will provide direct links to existing web-accessible information. NBI will maintain and update the site over time.

7.5.8 Controls White Paper

Based on a presentation by NBI's Technical Director at the California Emerging Technology Summit in 2006 on building controls as well as subsequent discussions, the PIER FDD Program Manager, agreed to provide support from the Market Connections budget toward the development of a Controls Guide that would provide effective guidance on controls system needs and approaches in buildings. It was understood that NBI would begin work on the Guide, but that additional funding would be required to complete the work. NBI has created a White Paper designed as a lead into the development and direction of the Guide, describing the role of controls and related building performance. FDD is clearly positioned as an integral part of building controls. NBI is assessing the potential for convening a National Controls Summit to address the issues that are raised in the White Paper.

7.6 Conclusions and Recommendations

7.6.1 Conclusions

The Market Connections work was successful in meeting the key FDD Program goals of advancing FDD further into the market and into regulatory arenas in California. NBI's Market Connections activities have helped create momentum that is likely to carry forward as the whole topic of achieving and maintaining building energy performance advances toward goals being established in California and elsewhere to create a path to zero net emission commercial buildings in 2030.

The key challenges remain of transforming the way buildings are designed, controlled, operated and maintained. As noted there is a lack of common definition or industry standards of what constitutes FDD capabilities within control systems in larger buildings. In smaller commercial buildings, effective control strategies are not obvious to many building operators. Limited attention by owners often means that potential problems with equipment performance are not acknowledged until something breaks or there is a loud enough occupant complaint about temperature and/or ventilation conditions. This is true for all sizes and types of commercial buildings. The mere presence of FDD information is not sufficient to cause actions to take place in many buildings. Transformation of owner/operator attitudes toward building performance is the critical ingredient in realizing the potential of FDD functionality. This is not a new observation or conclusion. It is a reminder of what remains to be done in the overall building performance market.

FDD is not fundamentally a standalone approach with its own specialized set of tools and black boxes. FDD must be viewed within the overall framework of whole building and subsystem controls, performance monitoring, and HVAC system operations and maintenance.

The US Department of Energy commissioned a 2006 report titled "Energy Impact of Commercial Building Controls and Performance Diagnostics: Market Characterization, Energy Impacts of Building Faults and Energy Savings Potential."[12]

The study's authors concluded that generally FDD could save between 5-30% of building energy use. This is a similar conclusion initially made about the energy savings potential of building commissioning, which is itself a diagnostic approach. Given the less than optimal operating conditions found in many buildings, a prominent FDD researcher has noted that savings of 15-30% were likely using diagnostics. Although a more closely bounded estimate is necessary, there is an acknowledgement that the potential energy savings benefits of FDD are not easily calculated, since, ultimately, individuals have to take action based on the information

[12] http://www.tiaxllc.com/aboutus/pdfs/energy_imp_comm_bldg_cntrls_perf_diag_110105.pdf

provided by FDD systems. Conditions in management outside the purview of building operations usually dictate the limits of the operations staff's ability to optimize building energy performance

There are a number of detailed related post-program follow-up recommendations that could be considered in California and nationally. The recommendations here focus mostly on higher level actions within California. The IOUs have the organizational capacity through the Emerging Technology framework to assess the benefits and costs of FDD. Recent regulatory calls in California for substantial IOU support of FDD benefit assessments will help drive FDD toward market adoption.

The recommendations made here closely parallel and support the recommendations recently developed through the CPUC's Strategic Planning Process and linked to the recently released "Preliminary Energy Efficiency Strategic Plan" by the California IOUs. In addition, the Western Cooling Energy Center, has proposed a comprehensive statewide FDD program that drew upon collaborative work between NBI and WCEC staff. Piecemeal efforts at establishing FDD in the market are less likely to succeed than a more structured, comprehensive statewide approach, such as has been proposed by the Cooling Center.

7.6.2 Recommendations for Post-Program Activities

7.6.2.1 Statewide Plan for FDD and Utility Emerging Technology Efforts

In California, the first step is for the IOU Emerging Technology (ET) Coordinating Council to consider a statewide action plan for incorporating diagnostics demonstration projects into each utility's ET program. A coordinated effort would have a far larger, and quicker, market impact than attempting to assess the benefits of FDD tools piecemeal. A Technical Advisory Group should be formed to identify commercially available and emerging FDD products, and develop a demonstration and evaluation framework to help increase confidence in the benefits of FDD in achieving and maintaining building energy performance. It is important to ensure that a variety of available and emerging products are evaluated. The results of this statewide effort would facilitate communication of FDD benefits to the buildings sector marketplace and establish the basis for utility pilot programs aimed at directly supporting FDD adoption. This work is critical to the next recommendation relating to FDD in Title 24. An overall approach is detailed in the California Public Utilities Commission Strategic Plan recommendations and in the Western Cooling Efficiency Center's comprehensive, statewide IOU FDD proposal.

7.6.2.2 Development of FDD as a Requirement in Title 24 Standards

In order for FDD to become a Title 24 Standards requirement, a substantive assessment of the benefits of existing FDD tools must be completed. This support is consistent with a CPUC Strategic recommendation to establish FDD requirements in the 2011 Title 24 Building Standards revision. The CPUC has described a number of activities in support of FDD adoption. A comprehensive action plan to implement the necessary assessments of FDD benefits through the IOUs has been proposed by the Western Cooling Efficiency Center as a result of the FDD

Roundtable held in 2007. The results of this work will enable consideration for FDD requirements in the 2011 Title 24 Standards revision.

7.6.2.3 Energy Efficiency at State Facilities

Through his Green Building Initiative (Executive Order S-20-04)[13], California Governor Schwarzenegger directed state agencies to make state-owned facilities 20% more energy efficient by 2015 and to benchmark state facilities with the Energy Star Portfolio Manager Target Finder. In order to achieve and maintain the overall savings goals, both physical plant efficiency and operational efficiency, have to be well managed. FDD will help state facility managers meet their operational efficiency goals. Three immediate steps related to FDD are recommended for the Department of General Services (DGS) consideration. PIER staff could communicate both directly to staff at the appropriate level at DGS.

1. Through the DGS "Green California" initiative, there should be an internal inventory of the available diagnostics capabilities that are embedded in the fleet of existing HVAC equipment and systems, owned or leased by the state, including small rooftop units to large built up systems. This review should take place within a parallel review of the equipment controls systems and how they are used operationally since that is where embedded diagnostics reside. A review of management practices regarding maintenance and service response to diagnostic information should also be done as part of the inventory. The physical inventory and management audit process will help further educate DGS staff on existing controls and FDD capability, as well as focus attention on the role of FDD in meeting the energy reduction goals in the Executive Order.
2. Review potential adoption of the Advanced Package Rooftop Unit (ARTU-Project 4) features by the DGS for inclusion in procurement specifications for rooftop unitary HVAC systems. PIER program staff should initiate direct communications on the ARTU with the DGS. The ARTU feature set, which includes FDD as well as other important field performance, maintenance and serviceability enhancements, should be formally assessed by DGS.
3. DGS staff should assess the benefits and cost of the new Lennox 'Strategos' 5-10-20 ton rooftop package HVAC units, which have a number of the ARTU features including some of the embedded FDD capabilities as standard. The efficiency claims (EER and IPLV) for the units make it the top rooftop unit line currently on the market taking efficiency past the Consortium for Energy Efficiency's Tier 3 level. The unit may also meet another PIER objective of developing air conditioners that are optimized for efficiency in hot dry climates.

7.6.2.4 Measured Performance

NBI is currently working with the California Institute for Energy and the Environment to refine a Measured Performance Case Study to be applied on two new buildings at the University of California Merced (UCM). The UCM case studies will provide a springboard to gaining

[13] http://gov.ca.gov/executive-order/3360/

information on the actual performance of a larger number of buildings nationally through the development of the template and validation of actual performance. This effort should include an assessment of the role of FDD within the building control system in maintaining building energy performance in the buildings to be studied.

7.6.4.5 National FDD Standards/Protocols

The California Energy Commission PIER Program, should initiate a project to work with the ASHRAE, the HVAC industry, controls companies and FDD researchers, to develop a minimum set of embedded FDD capabilities/protocols for small and large commercial HVAC equipment and systems. This is consistent with recommendations made in the CPUC, utility EESP and WCEC's FDD proposal. The lack of a national minimum FDD standard/protocol has been identified as a significant barrier to market understanding and adoption of FDD capabilities.

7.6.2.6 FDD Field Research-Part A

PIER should consider support of a field research project that would help determine the status of current diagnostics and point the direction to potential improvements in existing products and support commercialization of new, advanced tools such as Rooftop Unit Diagnostics-Project 5. For smaller commercial HVAC equipment, approximately 5-50 tons, a set of FDD capabilities have already been implemented by manufacturers typically related to operating conditions in the refrigeration cycle, air handling system and the economizer. There is little known about the effectiveness of these existing FDD features in the field, given that poor operating performance is so common. A better understanding of how building owners and HVAC service contractors use or think about existing diagnostics, and what improvements might be most beneficial to existing or new FDD approaches, is needed.

7.6.2.7 FDD Field Research-Part B

Specific follow up research is recommended aimed at determining the degree of typical operating performance degradation over time in unitary packaged rooftop systems. The results of the assessment could be linked to support of the performance enhancement and serviceability features defined in the ARTU. Research conducted through the PIER project "Integrated Design of Small Commercial HVAC Systems, Summary of Problems Observed in Field Studies of Small HVAC Units," October 2003, indicated a variety of performance problems in rooftop HVAC units that were 1-4 years old. Experience from California utility-funded refrigeration charge and airflow service programs continues to show performance degradation related to incorrect charge and poor airflow. Utility-sponsored rooftop unit service programs in California, the Pacific Northwest and everywhere such programs have been run, also encounter widespread economizer performance problems.